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The New York Power Authority's Energy-Efficient Refrigerator Program for the New York City Housing Authority—Savings Evaluation

ENERGY STAR® Partnerships Program

R. G. Pratt
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August 1997

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

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Pacific Northwest National Laboratory
Richland, Washington 99352

Summary

The New York Power Authority (NYPA) and the New York City Housing Authority (NYCHA) are replacing refrigerators in New York City public housing with new, highly energy-efficient models over a five-year period. This report describes the analysis of the energy cost savings achieved through the replacement of 20,000 refrigerators in 1996, the first year of the NYPA/NYCHA program.

The NYPA/NYCHA project serves as the core of a larger program designed to offer energy-efficient appliances to housing authorities across the country. The national program is a partnership between the U.S. Department of Energy (DOE) and the Consortium for Energy Efficiency (CEE). Starting with the 1997 refrigerator contract, this program invites other housing authorities to join NYPA in its volume purchase of energy-efficient refrigerators, at the same price and terms available to NYPA. Through these volume purchases, DOE's ENERGY STAR® Partnerships program hopes to encourage appliance manufacturers to bring more efficient appliances to the market and to provide volume purchasers with the per-unit price savings of a bulk purchaser. DOE asked the Pacific Northwest National Laboratory (PNNL) to establish a protocol for evaluating the savings achieved with the NYPA refrigerators. That protocol is summarized in this report.

NYPA identified the most life-cycle cost-effective refrigerator proposed by manufacturers in 1996 through a competitive procurement for a bulk purchase of 20,000 units, won by General Electric (GE) with a 14.4-ft^3 top-freezer automatic-defrost refrigerator rated at 499 kWh/yr. NYCHA arranged to be repaid by the U.S. Department of Housing and Urban Development (HUD) for program expenses in exchange for lower annual energy cost reimbursements, with savings to be demonstrated by a metering project. NYPA purchased and financed the refrigerators. NYPA's contractor Planergy installed the new refrigerators for NYCHA and recycled materials from the replaced units. The New York State Energy Research and Development Agency supported the metering effort, which was conducted by Synertech Corporation. PNNL was asked to conduct the savings evaluation for 1996 and 1997.

Each party in the program gains substantial value: residents of public housing receive a new and better appliance, NYCHA receives new refrigerators and can use the funds normally spent replacing them for other much needed improvements, NYPA receives goodwill with its third largest customer (NYCHA), and the federal government keeps the long-term energy cost savings and spurs voluntary development of new, efficient refrigerator designs.

Data Collection

The number of refrigerators replaced is based on NYPA's records of the number of new refrigerators installed. The models (and hence labels and sizes) replaced are based on Planergy's records of the model number of each existing refrigerator demanufactured. NYPA records show 20,000 GE refrigerators were delivered to NYCHA housing developments in 1996. Planergy shows 15,939 refrigerators were demanufactured. This difference is because a) some residents had their own refrigerator, b) some units were being remodeled and were empty, and c) some residents were not home to allow installation. In

these cases a new refrigerator was placed in storage at the housing development until it could be installed at a later date. Also, housing developments not scheduled for refrigerator replacement until future years were salvaging some of the existing units to replace some of their oldest refrigerators. The very old units being replaced at these other developments usually did not make their way into Planergy's demanufacturing system. Table S.1 summarizes the number of refrigerators in the program and the number of units metered.

Table S.1. Summary of NYPA Refrigerator Program Metering Effort

Characteristic	Existing Units Removed, (various models)	New Units Delivered (GE Hotpoint)
Number of Refrigerators	15,939[a]	20,000
Internal Volume (population weighted), ft3	12.6	14.4
DOE-Label Rating (population weighted), kWh/yr	903	499
Defrost type	Manual[b]	automatic
Indoor temperature (est. annual aug.) °F	78.7	78.7
Number metered		
Synertech, total	256	74
Data used, total	188	56
NYPA, total	56	
Data used, total	??	
Synertech, subtotal	30 (new or used?)	
Data used, total	17	

(a) Through December 31, 1996, remainder of installations proceeding rapidly.
(b) Vast majority of removed units had manual defrost.

The field monitoring activities conducted by Synertech included

- short-term metering of total energy consumption for refrigerators in use by NYCHA occupants for a period of approximately one week, for a sample of existing refrigerators (n=256) and the new GE high-efficiency replacement refrigerators (n=74)

- collecting refrigerator model numbers and snapshot data (at the beginning and end of the metering period) of key drivers for refrigerator energy consumption including indoor and refrigerator compartment temperatures, compartment temperature control settings, and visually estimated food loadings in each compartment

- supplementing the energy consumption data with a small sample metered with data loggers (n=30) to collect much more detailed 15-minute interval consumption data, including ambient air temperatures, refrigerator and freezer compartment temperatures, defrost cycles, and door openings and durations, as a basis for understanding these key effects as well as peak load impacts.

No formal sampling scheme was established; residents were recruited for metering on an ad hoc basis. Thus, the sample is not random in a formal statistical sense, but it is felt that a reasonably representative sample of the occupants' refrigerator usage was obtained.

Synertech also conducted tests in an environmental chamber to verify that the new refrigerators achieved their rated performance under the conditions of the DOE label rating test,[a] and to ascertain their efficiency as a function of ambient and compartment temperatures.

NYPA provided 15-minute total building electric demand records for 10 NYCHA developments to determine the time of day of building peak demands.

NYPA also conducted a compliance survey to determine refrigerator control settings before and after a campaign was conducted to lower them after it was found that the new units were set at colder-than-needed temperatures.

Analysis Procedure

The objective of this analysis was to estimate the annual energy and cost savings to NYCHA (at current NYPA electric rates) achieved by replacing existing refrigerators with the new GE model during calendar year 1996. Achieving a more general understanding of savings as a function of refrigerator label ratings, occupant effects, indoor and compartment temperatures, and characteristics (such as size, defrost features, and vintage) is the subject of data collection and analysis efforts for 1997. Therefore, except for the peak load impacts, the measured data utilized was primarily the weekly energy consumption and snapshot data.

PNNL's analysis had to account for four effects not directly represented in the raw data:

- Refrigerator energy consumption is largely proportional to the temperature difference between the compartments and the ambient indoor air, and indoor temperatures during the week-long metering periods do not represent annual average conditions.
- Part way through the metering period it was discovered that the new refrigerators were operating several degrees colder than the existing refrigerators, and the manufacturer's default control setting was lowered to compensate for this.
- Although the sample size is large, many more models of existing refrigerators were replaced than could be metered, and the efficiency of the existing refrigerators, as evidenced by their DOE-label ratings, varies widely (by more than a factor of two).

(a) DOE created the testing mandated by the Federal Trade Commission in the Energy Guide labeling program. These ratings refer to controlled consumption testing (no door openings) at an ambient temperature of 90°F. These label ratings are not intended to accurately predict field consumption but rather serve in a way analogous to miles-per-gallon ratings for automobiles.

- The refrigerators' share of the building's peak load (upon which electricity demand charges are based) is less than their share of the average building consumption, because the overall consumption by all other appliances increases more during peak periods than does a refrigerator's. So, cost savings for peak demand reduction must be accounted separately, instead of computed based on a blended-rate (the total electric bill for energy and demand charges divided by the number of kilowatt-hours).

To conduct the analysis PNNL performed the following steps:

1. Adjusted the measured consumption of each of the refrigerators from the indoor temperatures during the metering period to that which would occur under annual average conditions for the public housing population as a whole.

2. Constructed a relationship between refrigerator energy consumption and DOE-label rating so that consumption can be estimated for refrigerator models not represented in the metered sample.

3. Used this relationship to estimate savings for each refrigerator replaced, and estimated savings attributable to changing the new refrigerators' control settings from 5 to 2.

4. Estimated the energy consumption of refrigerators during the hours of peak building demand, and use it to compute the peak demand cost savings.

5. Used the records of the number of refrigerators of each model demanufactured, because efficiency varies by model, to compute an average total-per-unit savings for the 1996 program.

Results

Key results of the analysis are summarized here and in Table S.2.

Table S.2. Summary of NYPA Refrigerator Program Energy and Cost Savings

Refrigerator Group	Label Ratio	Energy		Demand		Total $/yr
		kWh/yr	$/yr	kW/mo	$/yr	
Consumption						
Existing (population weighted)	1.34	1,207	$42.71	0.147	$39.24	$81.95
New, control set @ 2	1.13	563	$19.93	0.068	$18.31	$38.24
New, Set @ 5	1.50	749	$26.51	0.091	$24.36	$50.87
New, control as found	1.26	629	$22.25	0.076	$20.44	$42.70
Savings						
If all new controls set @ 2		644	$22.78	0.078	$20.93	$43.71
Controls on new as found		578	$20.46	0.070	$18.79	$39.25

- NYCHA pays \$0.0354/kWh and \$22.31/kW each month in demand charges. ***NYCHA considers its energy cost based on an effective blended rate of \$0.085/kWh***. ***For the refrigerators,*** whose loads at the time of the building peaks are only slightly higher than their average load (1.064 times)***, a comparable blended rate of \$0.068/kWh was computed based on the 15-minute interval refrigerator data***. (Details of this calculation are presented in the body of the report.)

- Early data showed that ***the manufacturer's control settings of the new refrigerators (5 on a scale of 9) were producing very cold temperatures. They were subsequently adjusted downward to 2***, residents received fliers explaining the advantages of keeping them there, and NYCHA staff added this as an item of their annual inspection process.

- ***If all the new GE refrigerators had remained at a control setting of 2, as installed,*** then the program would have ***saved an average of 644 kWh/yr, worth \$43.71 per year per refrigerator*** when demand costs are included.

- NYPA's survey revealed ***an average control setting of 3.06, resulting in estimated savings of 578 kWh per year and an average 0.070 kW at peak demand per month (±10%, 90% confidence interval).*** The cost savings of \$39.25/yr represent a 9.1-year simple payback for the \$356 cost for purchase, installation, and recycling (excluding loan transaction costs).

- ***If the compliance with the targeted control setting was as good as at one of the two developments surveyed after the control adjustments, then the savings estimate would increase by about 7% to 619 kWh/yr (\$42.06/yr).***

- ***The new refrigerators are significantly larger than the average replaced unit (14.4 ft^3 compared to 12.6 ft^3)***. This provides considerable added amenity for the residents. It should be noted that savings would be even higher if the new refrigerators were the same size as the existing units. Consumption is not strictly linearly proportional to refrigerator size, but a simple estimate of the effect can be based on the ratio of their volumes. ***The additional energy savings that would have occurred had the new refrigerators been as small as those replaced is 172 kWh/y***r.

- Another similar qualitative ***amenity provide by the new refrigerators is automatic defrost***. ***Most of the existing units were manual defrost*** models. A simple comparison of the difference in historical DOE-label ratings for refrigerators of this size provides ***an estimate of the energy consumed by the automatic defrost cycle: around 140 kWh per year***.

- Previous ***studies of refrigerators in single-family dwellings showed the ratio of energy consumption to DOE-label rating to be about 0.9, whereas in this study the new and existing units have ratios of 1.3***. Single-family dwellings are typically much cooler than the annual average for the NYCHA apartments (78.7°F), have larger refrigerators, and may have fewer occupants, especially fewer home during the day. ***The difference in temperature explains a little more than 75% of the difference in the ratios; the remaining 25% may be explained by the number of occupants and their refrigerator usage behaviors.*** These issues are being addressed in 1997.

Acknowledgments

The authors wish to sincerely thank the staff of Synertech Corporation of Syracuse, New York, particularly Dr. Larry Kinney and Glen Lewis and their sponsor Norine Karins of the New York State Energy Research and Development Authority, for their efforts in collecting and managing the primary metered and survey data. Without their help as collaborators, our work would not have been possible. We also wish to thank the staff of Planergy, led by Dennis Flack, for their diligent collection of model numbers and counts for the recycled refrigerators.

Many others were involved in the monumental effort to manage and coordinate the overall refrigerator replacement program: Scott Brown and Dominick Luce of the New York Power Authority; Bill Steinmann, Mike Gray, and John Chu of the New York City Housing Authority; and John Glasby and Howard Siskind with Planergy. Our thanks go to Ed Wisniewski of the Consortium for Energy Efficiency, Tom Foley, and Graham Parker of Pacific Northwest National Laboratory who worked on program design.

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1.0 Introduction

The New York Power Authority (NYPA), the New York City Housing Authority (NYCHA), the New York State Energy Research and Development Authority (NYSERDA), and the U.S. Departments of Housing and Urban Development (HUD) and Energy (DOE) have joined in a project to replace refrigerators in New York City public housing with new, highly energy-efficient models over five years. This project is part of a larger effort sponsored by the Consortium for Energy Efficiency (CEE) and DOE to enable housing authorities throughout the United States to bulk purchase energy-efficient appliances. This document describes the analysis of the annual energy cost savings achieved from the replacement of 20,000 refrigerators in the first year of the program.

The roles of the various agencies involved and their contractors are summarized here.

- NYCHA arranged to be reimbursed for program expenses by HUD, who ordinarily pays NYCHA's energy bills, as long as the cost savings were demonstrated to pay for refrigerator purchase and installation costs. Savings beyond program expenses accrue to HUD. NYCHA also arranged and coordinated access to the apartments for the refrigerator installations.

- NYPA identified the most cost-effective refrigerator available through a request for proposals (RFP) issued to manufacturers for a bulk purchase of 20,000 units in 1996. This competitive procurement was won by General Electric (GE) with a 14.4-ft^3 top-freezer automatic-defrost refrigerator rated at 499 kilowatt-hours/year (kWh/yr). NYCHA then signed a contract for NYPA to purchase, finance, and install the new refrigerators, and demanufacture and recycle materials from the replaced units. NYPA managed the installation and demanufacturing (recycling) efforts of its subcontractor, Planergy.

- HUD agreed to reimburse NYCHA for the refrigerator purchase and installation costs. HUD also agreed that savings would be demonstrated by a metering effort, because accurate savings estimates could not be expected from the weather-adjusted billing analysis technique normally prescribed by HUD. Evaluating these savings is the purpose of the evaluation summarized here.

- NYSERDA funded and managed the metering effort, upon which these savings estimates are based, through a subcontract to Synertech.

- DOE helped develop and plan the program through the ENERGY STAR® Partnerships program conducted by its Pacific Northwest National Laboratory (PNNL). PNNL was subsequently asked to conduct the savings evaluation for 1996 and 1997.

Each party in the program gains substantial value. NYCHA receives new refrigerators on an accelerated schedule while avoiding the operational expense of their purchase and installation. NYCHA is then able to use the money normally spent replacing refrigerators on other much needed building improvements. Residents of public housing receive a new refrigerator, typically larger than their current refrigerator and with automatic defrost. NYPA receives goodwill and a long-term relationship with its third largest customer, NYCHA. NYSERDA promotes the energy industry in New York through the involvement of firms based in the state.

DOE and HUD expect this program to serve as a model for many similar programs being undertaken in the near future. HUD and U.S. taxpayers win because they receive energy cost savings in excess of the program cost over the lifetime of the replacement refrigerators. DOE spurs the voluntary development of new, efficient refrigerator designs by generating mass purchases of the most life-cycle cost-effective models U.S. manufacturers can produce. Finally, U.S. industry and the economy win because jobs and economic growth are promoted by the accelerated replacement of old refrigerators with the new, efficient models.

The NYPA/NYCHA program is key to achieving these results in that it establishes both a precedent for operating such a program and a protocol for evaluating the savings achieved in a manner that is transparent and fair to all parties. The 1997 NYPA contract with Maytag allows other public housing agencies to join in the volume purchase for up to 40,000 more refrigerators at the same price. Several similar programs are in the planning stages around the United States.

The remainder of this report is broken into four sections. Section 2 discusses the data collection efforts and other data sources used. Section 3 and Section 4 describe the analysis procedure and discuss the results. Additional details on these topics are contained in several appendices referenced in the text. Section 5 highlights the conclusions drawn from the analysis.

2.0 Data Collection

PNNL's calculation of the program cost savings involved the integration of several data sources:

- records of the number of new refrigerators installed and model numbers for each existing refrigerator that was demanufactured
- total energy consumption monitoring in the field for a period of about one week for a sample of new and existing refrigerators, along with one-time measurements of ambient indoor air and fresh food and freezer compartment temperatures
- detailed 15-minute time-series metering of refrigerators in the field
- tests of the new refrigerator in an environmental chamber over a range of operating temperatures
- a database of refrigerator characteristics including model numbers, DOE-label rating test results, rated volumes, defrost features, and year of production, as reported by refrigerator manufacturers
- daily outdoor temperatures (during field testing) and long-term-average monthly outdoor temperatures for New York City from National Weather Service data posted on the Internet
- time-of-use electrical load shapes for 10 NYCHA housing developments, and the energy and demand rates charged by NYPA.

The following sections describe these different types of data and how they were obtained.

2.1 Refrigerators Replaced

The number of refrigerators replaced are based on NYPA's records of the number of new refrigerators installed, and the models (and hence labels and sizes) replaced are based on Planergy's records of the model number of each existing refrigerator demanufactured. NYPA records show 20,000 GE refrigerators were delivered to NYCHA housing developments in 1996. Planergy shows 15,939 refrigerators were demanufactured. The difference in the number of models is explained by two effects.

1. Some residents refused to accept a new refrigerator, in many cases because they owned their own. In other cases, apartments were in the process of being renovated or remodeled to comply with access requirements for the handicapped, or the resident was not home to accept the refrigerator. In these cases, a new refrigerator was placed in storage at the housing development until it could be installed at a later date. These existing 4,061 refrigerators were not demanufactured, and therefore were not counted by Planergy.

2. Housing developments whose refrigerators were not scheduled for replacement until future years were salvaging some of the existing units in better condition to replace some of their oldest refrigerators. The very old units being replaced at these other developments usually did not make their way into Planergy's demanufacturing system to be counted. Of course, if the refrigerators were not demanufactured, no model number and hence no label rating could be determined. It is reasonable to assume that these refrigerators are represented by the average of those that were demanufactured. It is strongly recommended that, in the future, these housing developments bring old refrigerators to be recycled in equal number to those being salvaged (NYPA intends to enforce this in 1997). 1% of the new units were also intentionally placed in basements as spares.[a]

The rate at which refrigerators are being installed in apartments is shown graphically in Figure 2.1. Of the 20,000 refrigerators delivered in February 1996 to NYCHA housing developments, 15,939 were installed in apartments by NYPA by December 1, 1996. Figure 2.1 shows the rate at which the approximately 4,000 refrigerators placed in housing development basements are subsequently being moved into the apartments by NYCHA to replace existing units. Records show that over 1,000 (or 25%) were installed in December alone (indicated by the dark line). At this rate, nearly all of the new refrigerators would be installed by April 1, 1997.

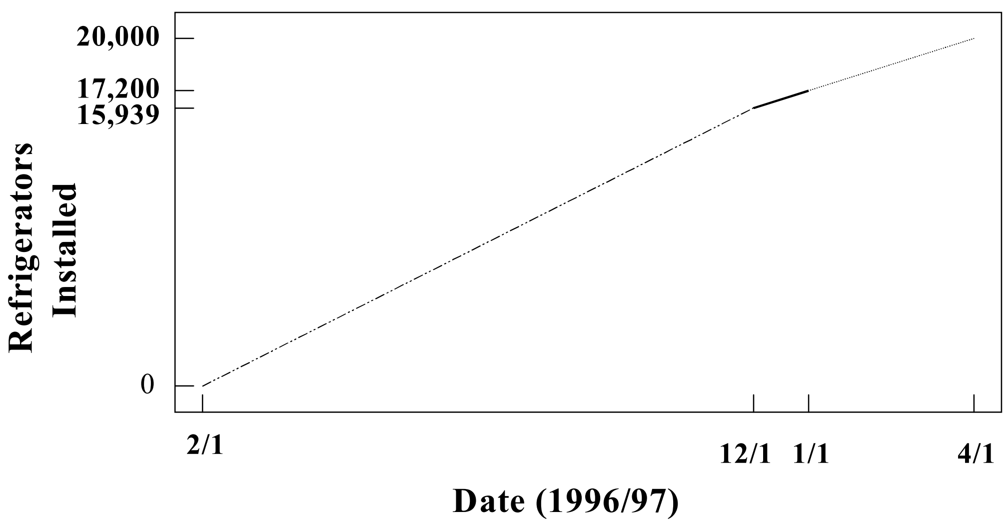

Figure 2.1. Rate of Refrigerator Installation in NYCHA Apartments

(a) It can be argued that if this were not done, then 1% of the existing units would have been retained as spares. If these were subsequently used to replace old refrigerators, savings would result. If these are used to replace new GE refrigerators that fail prematurely, then the failed units will not provide the expected cost savings. It is too early to tell whether 1% (200) of the new units can be expected to fail or be damaged by occupants. Whether savings for these 200 new refrigerators should be included is not considered in this report, but represents only a very small portion of the savings in any event.

2.2 Refrigerator Label Ratings and Characteristics Data

A database of refrigerator characteristics was used to look up DOE-label ratings for units replaced by the program. For many years, manufacturers have been required to provide DOE the results of energy consumption tests conducted in an environmental chamber for use as consumer label ratings (10 CFR 430, 1995). The label rating test consists of placing the refrigerator in a chamber maintained at an elevated temperature (90°F) to simulate door openings. After repeating the test at two control settings and measuring the resulting energy consumption and freezer temperatures, the results are interpolated to estimate annual consumption at a freezer temperature of 5°F. After testing several units off the production line, the average of their annualized consumption is issued as the label rating for a given model. DOE sets standards for maximum label ratings as a function of refrigerator volume. The Association of Home Appliance Manufacturers (AHAM) maintains an appliance database which lists each refrigerator by brand and model, DOE-label rating, rated volume, year of production, and the model's defrost features (AHAM 1990).

All possible model numbers do not appear in this database. Manufacturers use parts of model numbers to specify things like color, which side of the door is hinged, place of production, and other sub-model information. There also was a lapse in federally mandated reporting of label ratings in the late '70s, and labels were not required at all prior to 1975. Some manufacturers produce refrigerators that are essentially identical but are sold under a variety of brand names and have different model numbers. These appear separately in the database.

2.3 Field Data Collection and Chamber Tests

Synertech (Kinney 1997) installed meters on 256[(a)] existing refrigerators and 74 new GE high-efficiency replacement refrigerators to meter energy consumption over a period of approximately one week. In addition, NYPA collected similar data on 56 more refrigerators. For each metered refrigerator, NYPA and Synertech also collected a variety of characteristics information, including refrigerator model numbers and dimensions. Synertech also collected snapshot data on the first and last day of the 7-day metering period of key drivers for refrigerator energy consumption including indoor and refrigerator compartment temperatures using an infrared thermometer (radiometer), temperature control settings, and visually estimated food loadings in each compartment.

In addition, Synertech complemented the energy consumption data with a small sub-sample of refrigerators metered with data loggers (n=30) to collect much more detailed 15-minute interval data. In addition to power consumption, this included ambient air temperatures, fresh-food and freezer compartment temperatures, defrost cycles, and door openings and durations. This data was collected as a basis for understanding these key effects as well as peak load impacts. Weekly totals were also created from this data to add to the energy consumption sample.

(a) This is two less than the metered sample of 276 reported by Synertech. The disposition of the missing two data points is unclear.

No formal sampling scheme was established; residents were recruited for metering on an informal basis by knocking on doors or talking to residents or superintendents. Some attempt was made to sample various floors in the buildings because ambient temperatures may be higher on the upper floors.

Probably the most important consequence of the informal sampling is that, due to a lack of staff, no metering was conducted for a period of about one month during the time refrigerators were being replaced. During this month, installations were taking place at a housing development that was dominated by a particular model of old refrigerators that was not sampled in other developments. So, although this model of refrigerator was the fourth most common model replaced, it was not included in the metered sample.

Practical aspects of recruiting occupants and metering their refrigerators in New York City public housing also made it very difficult to meter a randomly selected sample of apartments. Occupants willing to allow access tended to be home when recruited, and cooperative with housing authority staff and the metering personnel. So, some self-selection bias is undoubtedly present in the sample. Although the sample is not random in a formal statistical sense, it is felt that a reasonably representative sample of the occupant's refrigerator usage was achieved. Metering will be more uniformly distributed in time during 1997, and an attempt to randomize the recruitment process will be made.

After screening for data quality problems, some metered records had to be eliminated because:

1. the metering period was less than 48 hours

2. critical data used in the analysis were missing (usually the snapshot temperatures or the compartment dimensions)

3. the 15-minute time-series data was clearly incorrect for part of the metering period

4. a few new refrigerators were metered at control settings other than 2 or 5, and only those at these settings were utilized in the analysis (as will be discussed in Section 4).

After these screens were applied, a sample of 188 existing and 56 new refrigerators (including 17 metered at 15-minute intervals) was used in the analysis.

The energy consumption levels measured for several refrigerators were noted as outliers but were not eliminated. Most of these were for existing refrigerators that had presumably malfunctioned. In at least once case, with measured consumption of over 5,000 kWh/year, Synertech tested the refrigerator in its environmental chamber and confirmed that the unit was malfunctioning and indeed was consuming that much energy. There were also a few new refrigerators with very low consumption, (e.g., they used one-third less energy than their DOE-label rating). These are harder to explain, but cool ambient indoor air temperatures, a low temperature control setting, and few door openings can produce such low consumption levels.

It should be noted that we examined the effect of these outliers on the results by repeating the analysis with and without them. To avoid biasing the results by manually filtering data, we defined outliers based on their label ratio (the ratio of their metered consumption to their DOE-label rating). Outliers were indicated when their label ratio was outside some number of standard deviations from the mean label ratio. When outliers were identified and removed on this basis, the savings estimates changed very little.[a]

Also, Synertech noted early in the metering effort that the infrared radiometer used to make the snapshot temperature measurements produced consistently warmer readings than a thermocouple, particularly at the low temperatures in the freezer compartment. A correction factor was produced based on these measurements, as discussed in Appendix A. Unfortunately, however, the manner in which the measurements were taken changed over the course of the metering, so this correction factor could not be applied with any confidence and the temperature readings were left uncorrected. They should still be indicative of the *relative* compartment temperatures, but their absolute value is somewhat suspect and their ability to explain the variation in consumption from one household to another is limited.

Synertech constructed its own environmental chamber and conducted a series of tests to verify that the new refrigerators achieved their rated performance under the conditions of the DOE-label rating test. These tests were then repeated over a range of chamber temperatures and compartment control settings to ascertain the effect of ambient and compartment temperatures on the new refrigerator's efficiency. A supplementary test involving cooling a known volume of water was also conducted to estimate the COP (coefficient-of-performance, analogous to efficiency) of the compression cycle.

2.4 Demand and Control Setting Compliance Data

NYPA provided 15-minute total building electric demand records for 10 NYCHA buildings in a previous July and January. These are the metered power consumption level at 15-minute intervals. This data was used to determine the time of day of building peak demands. NYPA also conducted a compliance survey to determine how many refrigerator controls were at various settings. This was done to determine the effect of a campaign to lower the settings because the temperatures in the new units proved colder than necessary.

(a) The savings were slightly lower because several of the high-consumption outliers consumed as much as several times their label rating, probably because of malfunctions, while the low-consumption outliers were only about 50% of their label rating. So, elimination of the high outliers had more impact than elimination of the low outliers, by lowering the mean consumption of the existing refrigerators and, hence, decreasing savings.

3.0 Analysis Procedure

The objective of the analysis activities was to estimate the annual cost savings to NYCHA (at current NYPA electric rates) achieved by replacing existing refrigerators with the new GE model during calendar year 1996. Achieving a more general understanding of savings as a function of refrigerator label ratings, occupant effects, indoor and compartment temperatures, and characteristics (such as size, defrost features, and vintage) is the subject of data collection and analysis efforts for 1997. Therefore, except for the peak load impacts, the measured data utilized was primarily the weekly energy consumption and snapshot data.

PNNL's analysis had to account for four effects not directly represented in the raw data:

- Refrigerator energy consumption is largely proportional to the temperature difference between the compartments and the ambient indoor air, and indoor temperatures during week-long metering periods do not represent annual average conditions.

- Part way through the metering period it was discovered that the new refrigerators were operating several degrees colder than the existing refrigerators, and the manufacturer's default control setting was changed to compensate for this.

- Many more models of existing refrigerators were replaced than could be metered with any meaningful sample, and the efficiency of the existing refrigerators, as evidenced by their DOE-label ratings, varies widely (by more than a factor of two).

- The refrigerators' share of the building's peak load (upon which electricity demand charges are based) is less than their share of the average building energy consumption, because consumption by other appliances increases more during peak periods than does refrigerator consumption. So cost savings for peak demand reduction must be accounted separately, instead of computed based on a blended rate (the total electric bill for energy and demand charges divided by the number of kilowatt-hours).

To conduct the analysis, PNNL performed the following steps:

1. Adjusted the measured consumption of each of the refrigerators from the indoor and compartment temperatures during the metering period to that which would occur under annual average conditions for the public housing population as a whole.

2. Constructed a relationship between refrigerator energy consumption and DOE-label rating so that consumption could be estimated for refrigerator models not represented in the metered sample.

3. Used this relationship to estimate savings for each refrigerator replaced and estimated savings attributable to changing the new refrigerators' control settings.

4. Estimated the electricity consumption of refrigerators during the hours of peak building demand, and used it to compute the peak demand cost savings.

5. Because the efficiency of the existing refrigerators varies widely, we used the records of the number of refrigerators of each model demanufactured to compute an average total per-unit savings for the program in 1996.

The key steps in our analysis processes are summarized below and in Appendices A through G. In Sections 3.2 and 3.3, two issues not addressed in the savings estimation procedure are discussed—performance degradation over time and heating/cooling interactions.

3.1 Analysis Overview

The steps we followed in conducting our analyses are outlined below.

Step 1. Adjust Metered Consumption for Annual Average Consumption

- Develop a relationship between indoor and outdoor temperatures for public housing in New York City based on the snapshot temperature data collected by Synertech and the daily outdoor temperature records from the National Climate Data Center. Then use long-term average monthly outdoor temperature data to estimate an annual average indoor temperature for the typical apartment.

- Compute a weighted compartment temperature for each metered refrigerator by computing a surface-area-weighted average of the observed fresh-food and freezer temperatures. Assume it remains essentially constant throughout the year.

- Compute the average of the weighted compartment temperatures for all the existing metered refrigerators and assume this temperature is typical of all refrigerators in New York public housing.

- Estimate the annualized consumption of each metered refrigerator as if it were operated in the conditions of the average housing unit. Two methods were used to do this. In the first (linear) method, each refrigerator's metered consumption is multiplied by the ratio of 1) the temperature differences (between the indoor and weighted compartment temperatures) for the annual average conditions in New York, to 2) the conditions measured at the beginning and end of the metering period. In the second (non-linear) method, we used a curve of refrigerator load as a function of the indoor and weighted-average compartment temperature difference, based on Synertech's chamber tests of the new GE refrigerator. These methods are described in more detail in Appendix B.

Step 2. Develop a Relationship Between Consumption and DOE-Label Rating

This relationship is needed so that consumption can be estimated for refrigerator models not represented in the metered sample.

- Divide the annualized consumption estimate for each metered refrigerator by the label rating for that model to form a consumption/label ratio.

- Demonstrate that no statistically significant differences in the *ratios* are found between various models of refrigerators with sample sizes greater than 10. That is, if labels are taken into account, no difference between the performance of various models of existing refrigerators can be demonstrated.

- Construct a relationship between the refrigerator energy consumption and label rating in New York public housing based on a linear regression estimate. Use it to estimate the average annual energy consumption of each model of existing refrigerator replaced.

Step 3. Estimate Energy Savings

- Using this relationship, compute the per-unit energy savings for each model replaced (including those not represented at all in the metered sample). Do this based on the difference in the average annual consumption estimate for the model and the average of the annualized consumption for the new refrigerators set at the program's temperature control setting.

- Use NYPA's survey of refrigerator temperature control settings, before and after the campaign to change them to a setting lower than the manufacturer's recommendation, to determine how many occupants left the control setting unadjusted. Compute the fraction of the refrigerators that would be at the manufacturer's recommended setting (5) and those at the program's control setting (2) to match the average control settings surveyed for these time periods.

- Estimate the energy consumption of the new refrigerators as the weighted average of the annualized energy consumption for refrigerators at the manufacturer's recommended setting (5) and those at the metered program's control setting (2), such that the weighted average control setting equals the average control setting found in NYPA's post-installation survey.

- Estimate the energy savings as the difference in the adjusted energy consumption of the existing and new refrigerators.

Step 4. Estimate Peak Demand Savings

- Analyze time-of-use data for typical NYCHA buildings to determine the hours of the day when peak loads occur. The approach used for this is discussed in Appendix C.

- Analyze the metered 15-minute refrigerator time-of-use data to determine the average load factor at the time of the building peak, i.e., the ratio of consumption during peak hours to the average hourly consumption for the year (as calculated not metered). Do this for both summer and winter seasons. The details of this are also discussed in Appendix C.

- Compute the peak load dollar savings for each model of existing refrigerator as the product of the average load factor, the load savings estimate for each model, and the peak demand rate charge.

Step 5. Estimate Total Per-Unit Savings

- Compute the total per-unit savings for each model of existing refrigerator replaced as the sum of the energy savings times the kilowatt-hour rate paid by NYCHA, plus the 12 monthly peak-load savings times the peak demand charge paid by NYCHA.

- Compute total program savings on a per-unit basis by adding up the total per-unit savings for all refrigerators replaced and demanufactured for which label ratings could be found and dividing by the total number of these refrigerators. This implicitly assumes that, when either a model number was unknown or a label rating could not be found for an existing refrigerator, its energy consumption was equal to the population-weighted average (mean) of all those replaced whose labels were found.

- Compute the confidence interval around the savings estimate from the variance explained by the relationship of energy consumption to DOE-label rating. The method used to compute the confidence interval is discussed in Appendix D.

3.2 Persistence of Savings

The persistence of savings for the program should be accounted for in overall savings estimates. However, at this point there is little to indicate how persistent they will be. Other studies have noted degradation of refrigerator performance over time. It seems reasonable to assume that the absolute rate of degradation is the same for the existing and replacement refrigerators. Then the difference between the consumption of the new refrigerators and the replaced refrigerators will remain constant over time, as shown in Figure 3.1.

This assumption of constant *absolute* rates of degradation corresponds to degradation modes not affected by the relative efficiency of the refrigerators, such as door seal leakage in refrigerators with similar compressor efficiency. Loss of insulation quality, compressor efficiency, or heat exchange effectiveness may be better reflected in similar *relative* degradation rates, that is, by a similar *percentage* degradation per year for both classes of refrigerator. Because the replacement refrigerators are efficient, their *absolute* degradation rate would be smaller in this case, and the slope of the degradation line for the replacement refrigerators would be lower than for the existing refrigerators.

3.3 Heating/Cooling Interactions

Because the replacement refrigerators use less energy, they will give off less heat during operation than the existing refrigerators. The impact of this reduction in operational heat would be increased winter heating loads and decreased summer cooling loads in the apartments. However because public housing unit temperatures are generally not controlled by individual thermostats, but rather are set for the building as a whole, and because most public housing is not air conditioned, it is unlikely that thermostat settings will be changed from current levels as a result of this program. Therefore the impacts are likely to be small so we did not attempt an analysis of heating and cooling interactions resulting from the reduced level of heat given off by operation of the replacement refrigerators.

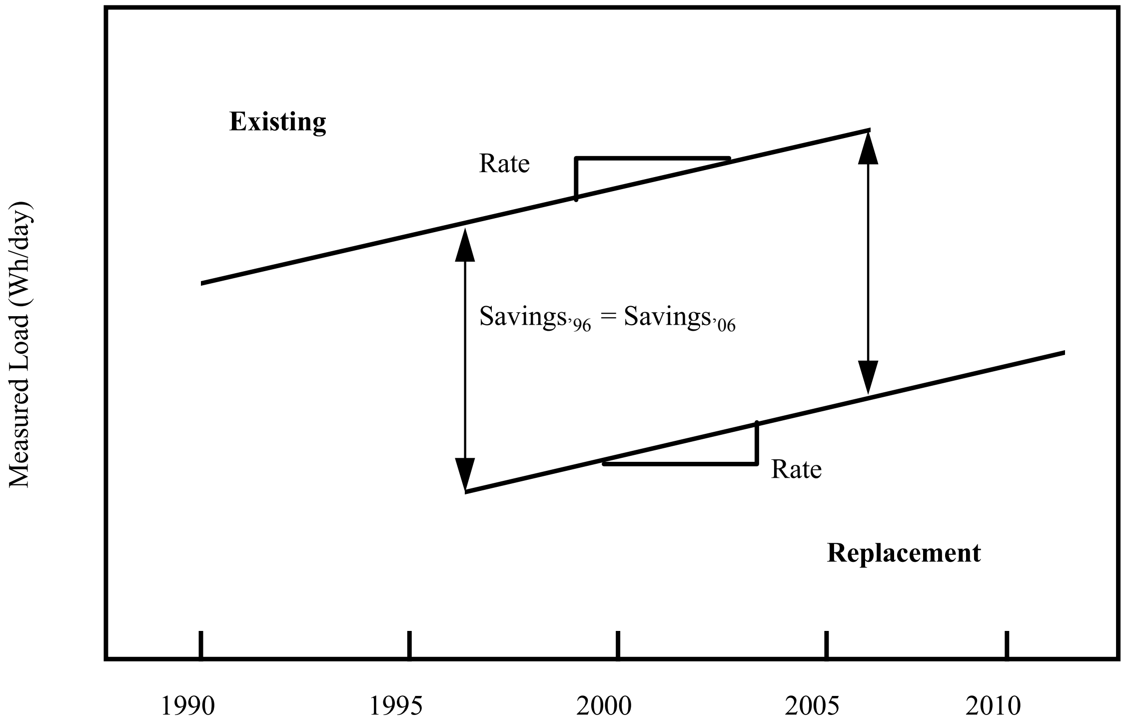

Figure 3.1. Effect of Refrigerator Performance Over Time on Savings (assuming equal absolute degradation rates)

4.0 Results

The results of the analysis are summarized in this section.

4.1 Comparison of New and Existing Refrigerator Characteristics

A comparison of the characteristics of the new and average existing refrigerators is presented in Table 4.1. NYPA records show 20,000 GE refrigerators were installed in 1996, while Planergy shows 15,939 refrigerators were demanufactured (see Section 2.1, Refrigerators Replaced). As evidenced by their much lower label rating (499 kWh/yr), the new refrigerators are much more efficient than the average refrigerator replaced by the program.

Table 4.1. Characteristics of the New and Existing Refrigerator Populations

Characteristic	Existing	New	Difference
Refrigerator Count	15,939	20,000	-4,061
Internal Volume (population weighted), ft^3	12.6	14.4	-1.8
DOE-Label Rating (population weighted), kWh/yr	903	499	404

The new refrigerators are significantly larger than the average replaced unit (14.4 ft^3 compared to 12.6 ft^3). This provides considerable added amenity for the residents. Because refrigerator heat loss and hence energy consumption are directly proportional to surface area, savings would be even higher if the new refrigerators were the same size as the existing units. A simple estimate of the extra energy savings that would have occurred had the new refrigerators been as small as those replaced (based on the ratio of the volumes) is 72 kWh/yr.

Another qualitative amenity the new refrigerators provide is automatic defrost. Most of the existing units are manual defrost models. A simple comparison of the difference in historical DOE-label ratings for refrigerators of this size provides an estimate of the energy consumed by the automatic defrost cycle of around 140 kWh per year.

4.2 Indoor Air Temperatures

The indoor air temperature in NYCHA apartments goes through strong seasonal variations. The indoor temperatures for each metered refrigerator are plotted as a function of the daily average outside air temperature for the period metered in Figure 4.1. Note that these indoor temperatures are not literally daily averages, but instead are the average of snapshot measurements taken at the beginning and the end of the metering period. The daily average outside temperatures are determined from National Climatic Data Center weather data for the corresponding period.

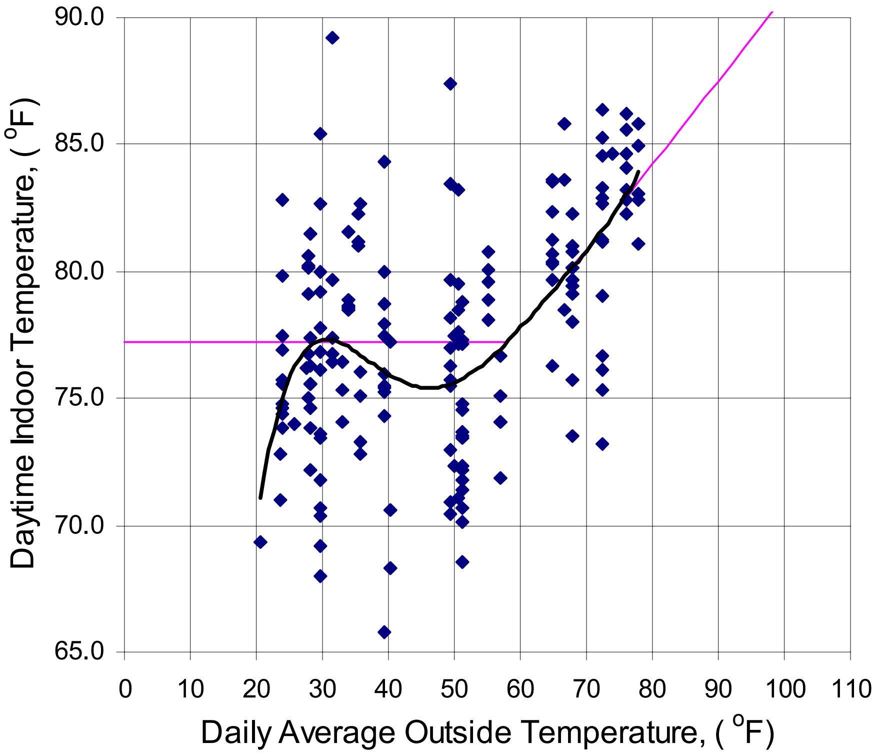

Figure 4.1. Relationship of Indoor and Outdoor Air Temperatures in NYCHA Housing

The apartments are very warm on average, even in winter. This is because the units do not have heating thermostats, and the superintendents are required to meet temperature requirements in the coldest apartments. The average indoor air temperature was about 77^{o}F during winter months; summer temperatures rose to an average of 83^{o}F in July. Note that the warm indoor temperatures actually increase savings, because, although energy consumption increases in both the new and existing refrigerators, consumption increases in the existing refrigerators faster because they are not insulated as well.

The curved line represents a polynomial fit to the data. It indicates a general upward trend above about 55^{o}F. Despite the considerable scatter in the data, we interpret this to be representative of indoor temperatures that are controlled in the winter through heating, yet continue to rise in the summer because of the lack of air conditioning. We represent this by a constant indoor temperature when it is colder than 58^{o}F outside and a steadily increasing indoor temperature when it is warmer outside. This is shown by the straight lines superimposed on the plot. We use this segmented linear model to estimate the indoor air temperature of the average NYCHA housing unit at any outdoor air temperature.

The segmented-linear model is used to determine an annual average indoor temperature. Average monthly outdoor temperatures (over 30 years) are used as inputs. The resulting predicted monthly indoor temperature is shown in Figure 4.2. A simple average of these 12 predicted temperatures is used to represent the annual average indoor temperature for NYCHA apartments, 78.7^{o}F.

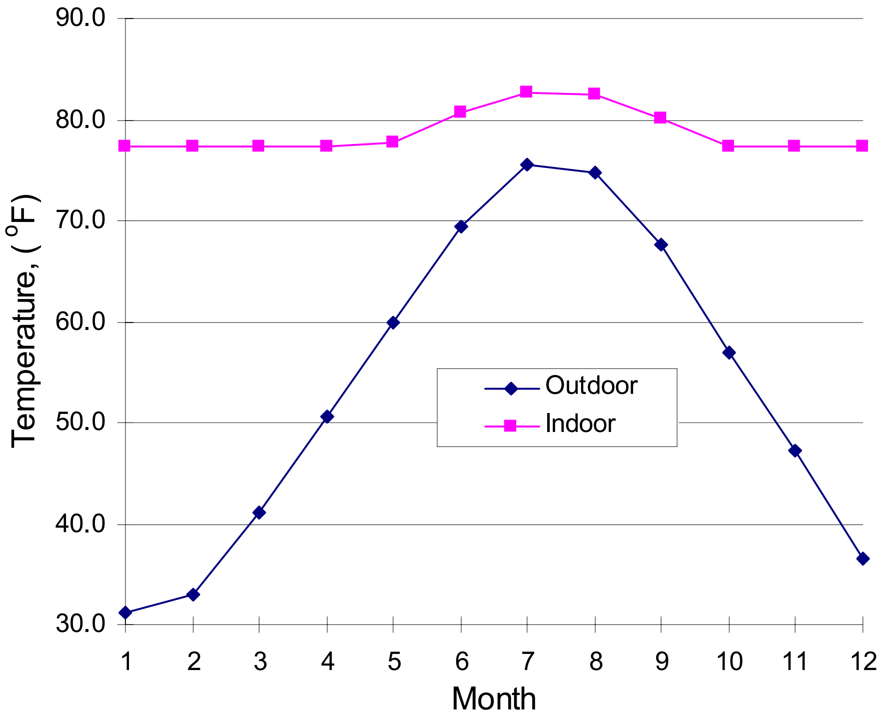

Figure 4.2. Average Monthly Indoor Air Temperature for NYCHA Apartments

4.3 Refrigerator Control Settings and Temperatures

The average of the weighted compartment temperatures (a surface-area weighted average of the fresh-food and freezer compartment temperatures) in the sample of existing refrigerators was 39.3°F. The new units ran cooler when operated at the manufacturer's factory control setting of 5. The average weighted compartment temperature was 1.2°F cooler, and the freezer compartments were 2.5°F cooler than the existing units. The cooler freezer temperatures in the new refrigerators may be caused by a poor setting for the splitter damper that allocates cold air to the two compartments when the compressor is on.

Consequently, NYPA began changing the new refrigerator's temperature controls to a setting of 2 at the time of installation, and NYCHA began an education campaign to keep them there (and change those already installed). NYPA subsequently performed a survey for compliance with the adjusted control settings. The purpose of this survey was to determine how many residents changed their control settings after installation.

The results of this survey are summarized in Table 4.2. Prior to the adjustment campaign the average control setting was 4.56; after the campaign the setting averaged 3.06. The table shows that most occupants (74%, or 25 of 34) did not change their control setting from 2 after the campaign began. Of those that did change their setting, 18% changed it to 7 (6 of 34), 3% each changed it to 5, 4, and 3 (1 of 34).

Table 4.2. Control Setting Adjustment Compliance Survey Results

Housing Development	No. Refrigs. Found at a Control Setting						Avg. Control Setting	Equiv. % Set At	
	2	3	4	5	7	All		2	5
Fulton	2	1	0	4	2	9	4.56	15%	85%
Subtotal, before campaign	2	1	0	4	2	9	4.56	15%	85%
Bronxdale	13	0	0	4	2	19	3.16	61%	39%
Subtotal, during campaign	13	0	0	4	2	19	3.16	61%	39%
Adams	9	1	0	1	5	16	3.81	40%	60%
Ravenswood	16	0	1	0	1	18	2.39	87%	13%
Subtotal, after campaign	25	1	1	1	6	34	3.06	65%	35%

It is notable that the majority of the changes to the control settings occurred in the Adams development, with much different results in Ravenswood. A larger survey might reveal the changes at Adams to be atypical, resulting in increased savings.

Because we have large samples of new refrigerators metered with their control settings at 2 and at 5, we compute the fraction of the population that would be at both 2 and 5 to produce equivalent average settings. This implicitly assumes a linear relationship between control setting and consumption. The average setting before the campaign is equivalent to 15% of the controls being at 2 (and the rest at 5), while afterwards this rose to 65%. This is shown in Table 4.2. For example, the calculation for the subtotal after the campaign is computed from

average control setting = (25*2 + 1*3 + 1*4 + 1*5 + 6*7) / 34 = 3.06 (n=34)

no. set at 5 (to produce average control setting) = (3.06 – 2) / (5 – 2) = 0.334

checking: 0.334*5 + 0.647*2 = 3.06

We will report savings at both a control setting of 2 and at the average control setting of 3.06 in Section 4.7.

4.4 Temperature-Adjusted Energy Consumption

The metered consumption of each refrigerator was adjusted as if it were operated at the average annual indoor temperature, 78.7^{o}F. As a check to ensure that the linear and non-linear methods (discussed in Section 3, Analysis Procedure and Appendix E) do not produce significantly different results, we used them both and compared the results. We also examined the effect of adjusting all the metered consumption data to a common weighted compartment temperature: the average of all the existing units. The results show that the savings estimates are not significantly affected by these methodological variations, as documented in Appendix E.

We used the results from the linear method because it does not depend on any assumption about similarity of the compression cycle COPs (coefficient of performance) in the new and existing units.

Practical considerations suggested that we adjust consumption only for the average annual indoor air temperature. This is because adjusting to a population-average compartment temperature tends to remove the effect of changing the control settings from 5 to 2 in the new GE units, and this is a key result desired from the analysis. After these adjustments were made, we computed a label ratio by dividing the adjusted consumption of each refrigerator by its DOE-label rating.

We then compared the savings estimates that resulted from conducting a stratified analysis and a model-based analysis. In the stratified analysis, we separately analyzed each group, or stratum, of existing refrigerators that were determined to be identical for the purposes of this study. That is, based on their model numbers, they were found to be produced by a common manufacturer, had identical label ratings and defrost features, and were produced in the same or adjacent years. If so, they were grouped to define a stratum and their consumption was averaged. As a result of the stratification process, all the metered refrigerators were grouped into one of 29 strata or, if less than a minimum sample of a stratum was metered, it was arbitrarily assigned to a catch-all strata.

Our minimum sample threshold to define a stratum as being metered was set to two; 37% of the replaced refrigerators were placed in the catch-all strata. For these refrigerators we assumed that their label ratio was the same as the population-weighted average label ratio of the existing refrigerators in metered strata.

In both approaches, if no DOE-label rating was available, we simply assumed the energy consumption of a refrigerator was equal to the population-weighted average energy consumption of the metered refrigerators (1,207 kWh/yr).

The problem with the stratified analysis is that few strata had enough metered representatives to provide good consumption estimates. Only four of the 29 strata had a sample with more than 10 refrigerators, and 19 strata had samples with less than 5. We found during the course of the year that savings estimates for the whole program could change by as much as 10% when just a few data points were added. This is because if a stratum has only a small sample and an outlier is added to it, then the mean for the stratum changes a lot. If this stratum also represents a large number of replaced refrigerators, and carries a lot of weight in the final result, the savings estimates could change a lot. The variance within strata was also noted to be very high. The standard error of the estimate of the average energy consumption level was over 100 kWh/yr for 15 of the 28 strata, and over 150 kWh/yr for 8 of the strata (see Table E.2 in Appendix E). This did not lend confidence in using the mean of each strata to represent large numbers of replaced refrigerators and led us to use a model-based approach to represent the replaced refrigerators.

In the model-based analysis, all refrigerators are assumed to perform in the field about the same relative to their DOE-label rating. That is, the average label ratios of all strata are about the same.

We demonstrate the validity of this assumption in Figure 4.3. This is a box plot[(a)] comparing the distribution of the label ratios in the five strata with the largest metered samples (n>9). Each box has a notch indicating the 90% confidence interval of the stratum. If the range of any of these notches overlap for any pair of strata, this is interpreted as indicating that the label ratios of the two strata do not differ in a statistically significant way. (The new refrigerators also form a "stratum" for this purpose.)

It can be seen that only the first stratum is different, and it is only different from the last stratum. The confidence intervals of the other six strata overlap, indicating they are statistically similar. On this basis, we judge that there are not statistically demonstrable differences in performance of one model of refrigerator compared to another that are not explainable by differences in their DOE-label ratings.

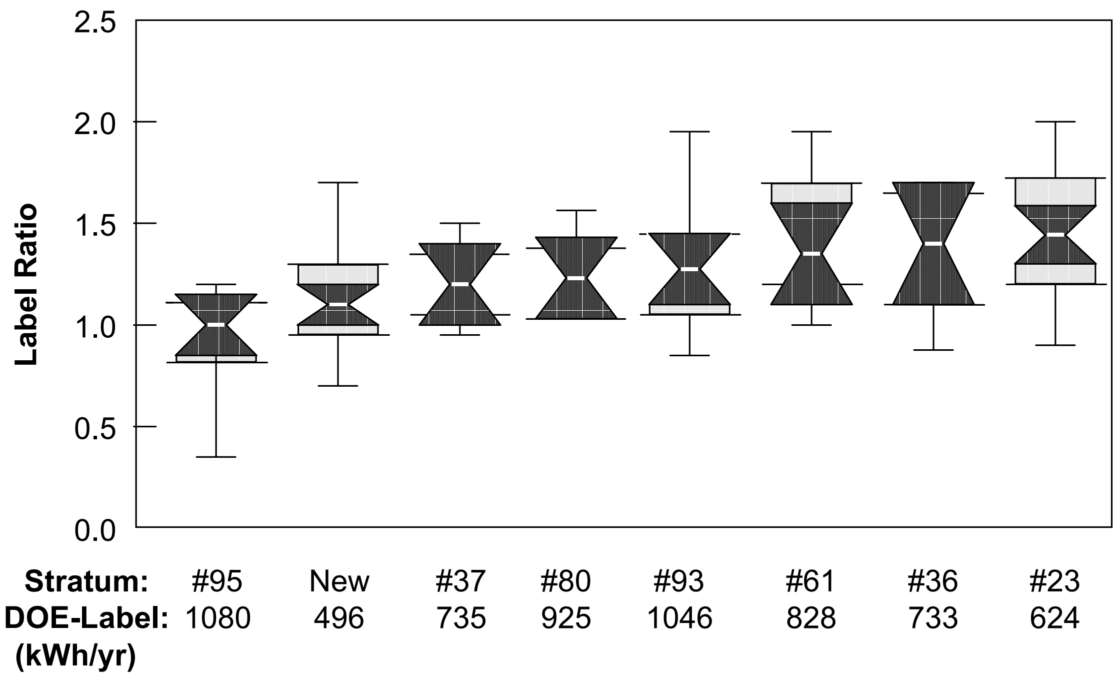

Figure 4.3. Distribution of Label Ratios for Strata with Large Samples

(a) In a box plot, the median of each stratum is shown as the "waist" of the notch in the middle of the box. The extent of the box above the median indicates the 3rd quartile of the data (from the 50th to the 75th percentiles), while the extent of the box below the median indicates the 2nd quartile (25th to 50th percentiles). The ranges of the upper and lower quartiles are shown by the extent of the lines extending up and down from the boxes. The confidence interval includes the range shown by the angled notch above and below the median "waist." In some cases this confidence interval overlapped the upper or lower quartiles. If the notch exceeds the extent of the quartiles, they can still be seen by looking for the lines extending from sides of the notch that indicate their extent. Outliers, defined as data points outside 2.5 standard deviations from the mean, are not shown.

We then constructed a regression-based relationship between metered consumption and label rating using all the metered refrigerators. This relationship is illustrated in Figure 4.4. The model only explains a fraction of the variance (R^2 of 0.18, or 18%) caused by the high scatter in the data already noted. However, the t-statistic on the slope is 6.1, indicating that it is statistically quite significant. We tried adding several other variables to this model to improve it, including control settings as a fraction of the dial range, food loading levels, defrost features, year produced, and rated volume. None provided any statistical benefit. We attribute the unexplained variance to wide ranges in occupant behavior with respect to the number and duration of door openings and food loadings. Variations in refrigerator condition and indoor humidity levels can have strong effects; maintenance (coil cleaning, defrosting, etc.) could also have an effect.

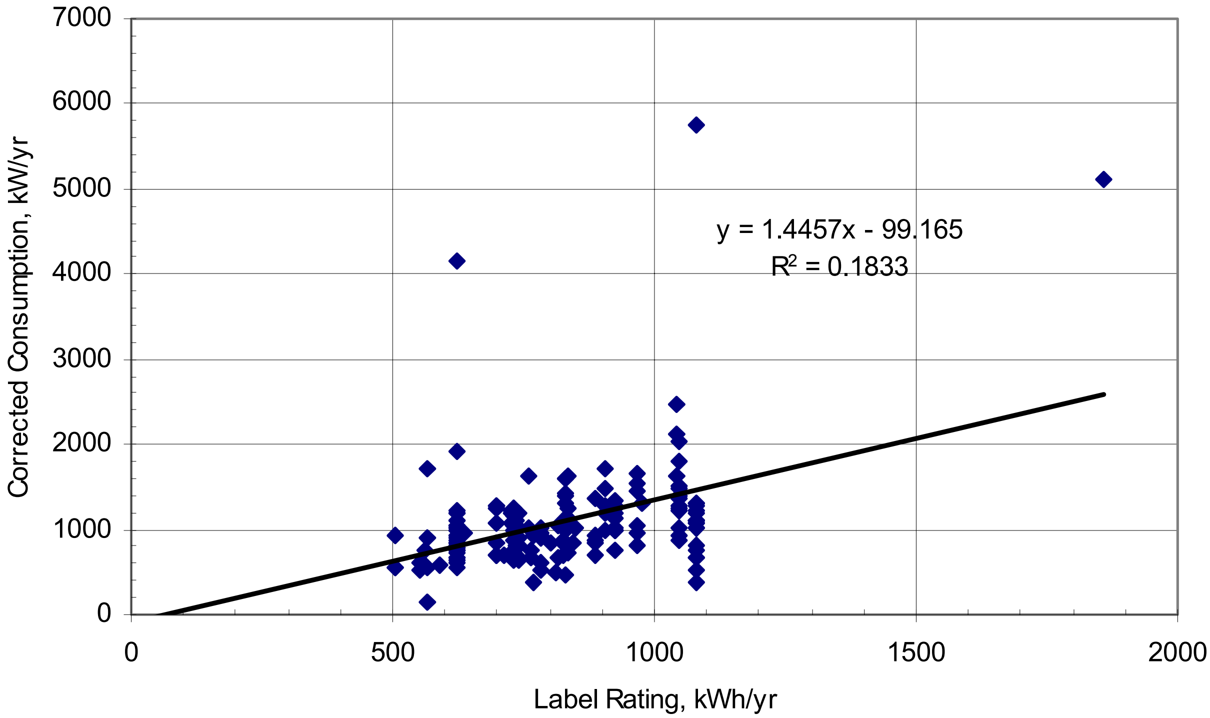

Figure 4.4. Relationship of Consumption to Label Rating for Existing Refrigerators

Other field metering studies have found label ratios of about 0.9, whereas in this study the new and existing units are at 1.3. The other studies are of single-family dwellings, which are much cooler during the course of the year, on average. The difference in temperature explains about 75% of the difference. Other factors may include the small size of these refrigerators, the high efficiency of the new units, and degradation in the existing units. This is discussed at greater length in Appendix F.

4.5 Demand Savings

Data from 10 NYCHA buildings with 15-minute load data metered by NYPA were examined. Their peak loads occur at an average of 9 pm in the summer and 7 pm in the winter. For the 17 refrigerators metered at 15-minute intervals for about one week, the average of their load shapes (hourly consumption divided by average consumption during the metering period) is shown in Figure 4.5. The raw data was noted to produce a very irregular load shape, unlike the smoother load shape that would be expected from the average of a larger sample (and/or a longer metering period). So, the data was smoothed using a rolling average over a 75-minute time window. We used this somewhat smoother load shape, also shown in Figure 4.5.

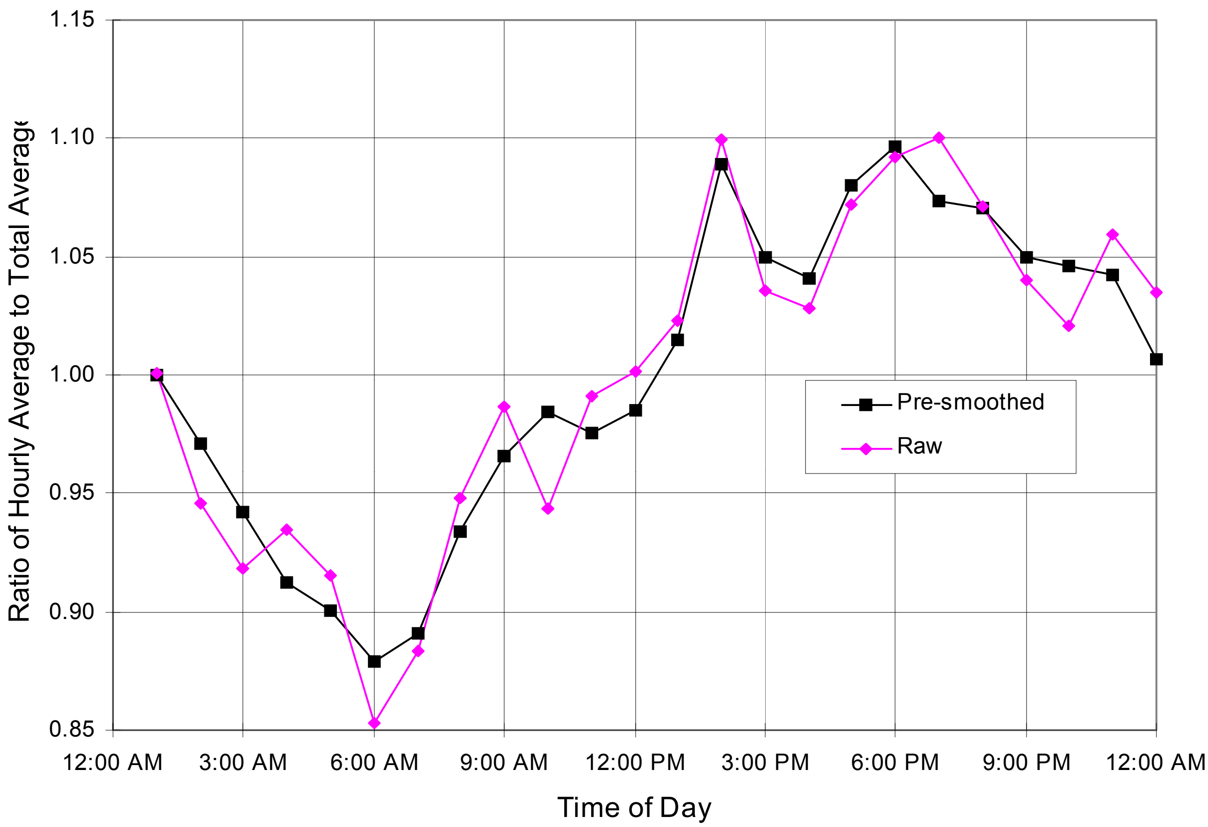

Figure 4.5. Average Daily Load Shape for 17 NYCHA Refrigerators

Only five were metered in the winter season. Given the high degree of variability exhibited by the full sample of 17, we did not have confidence in differentiating winter and summer refrigerator load shapes with this data. Approximating the time of the building peak demand as an equal number of winter and summer months, the average annual load for these peak hours was 1.064 times higher than the average load. Given the short duration of the metering and the small sample size, the demand savings estimates are relatively uncertain (and could be higher). Metering in 1997 will all be on a 15-minute interval basis, so these estimates should become more precise in the future.

4.6 Cost of Electricity

The energy and cost savings for the refrigerator replacements in 1996, which are summarized in Section 4.7, are based on NYPA's electric rates for both energy (kWh) and monthly peak demand (kW), including distribution surcharges applied by Consolidated Edison. NYCHA considers its energy cost on the basis of an effective blended rate of $0.085/kWh. They compute this by dividing the total electric bill by the kWh consumed. This is a useful simplification, but it is not the basis upon which they are billed. The blended rate is only accurate for computing the value of savings from efficiency improvements in equipment or loads that have the same ratio of energy to peak demand as the total electric consumption of the housing development.

For the refrigerators, a similar blended rate can be computed. Using the existing refrigerators as an example, the energy cost of a year's operation at 1,207 kWh/yr is $42.69/yr. The average demand over the year is 0.138 kW (1,207 kWh/yr divided by 8,760 hours per year). As discussed previously, the 15-minute data show that, at times of building peak demand, the refrigerators' loads are 1.064 times larger than average, or 0.146 kW. Because this is billed 12 months per year at $22.31/kW, the demand cost for the refrigerator is $39.25 per year. The total annual cost to operate the refrigerator is thus $81.91. Dividing this by the 1,207 kWh consumed gives a blended rate for refrigerators of $0.068/kWh.

The blended rate for refrigerators is lower than the housing development's overall blended rate because the buildings' total load during peak hours was about 1.6 times the average, while the refrigerators were much closer to their average load (1.064). Performing a similar calculation the energy the *whole building* consumes yields the building's blended rate

(1 kWh/yr * $0.0354/kWh +
1 kWh/yr / 8760 hr/yr * 12 month/yr * $22.31/kW-month * 1.6 ratio of peak to average)
/ 1 kWh = $0.084/kWh

4.7 Savings

Table 4.3 shows the average savings per refrigerator if all the new GE refrigerators had remained at a control setting of 2, as installed. Then the energy savings would have been the difference between the average consumption of the existing refrigerators (1,207 kWh/yr) and the GE refrigerators operated at 2 (563 kWh/yr) which equals 644 kWh/yr. The savings that could be achieved if all residents comply with NYCHA's directive to keep the control settings at 2 are an average $43.71 per year per refrigerator (all costs and savings are reported in 1996 U.S. dollars).

Table 4.3. Savings if All New Refrigerators Were Set at 2

Refrigerator Group	Label kWh/yr	Label Ratio	Energy kWh/yr	Energy $/yr	Demand kW/mo.	Demand $/yr	Total $/yr
Existing	903	1.34	1207	$42.71	0.147	$39.24	$81.95
New, Set @ 2	499	1.13	563	$19.93	0.068	$18.31	$38.24
Savings, New All @ 2			644	$22.78	0.078	$20.93	$43.71

We assume that the new refrigerators will remain at an average control setting of 3.06, as indicated by NYPA's survey (Table 4.2). This is computed as the weighted average of 65% of the savings when the new refrigerators were set at a control setting of 2 and 35% of the savings when they were at a control setting of 5. As shown Table 4.4, on this basis the savings for the average refrigerator replaced in the program are estimated as 578 kWh per year and the demand savings average 0.070 kW per month. This represents $20.46 per year in energy cost savings and $18.79 per year in demand cost savings, a total of $39.25 per year. The 90% confidence interval in the savings estimate was computed at ±10%, as documented in Appendix D.

Table 4.4. Population-Weighted Energy, Demand, and Cost Savings

Refrigerator Group	Label kWh/yr	Label Ratio	Energy kWh/yr	Energy $/yr	Demand kW/mo.	Demand $/yr	Total $/yr
Existing	903	1.34	1207	$42.71	0.147	$39.24	$81.95
New, Set @ 2	499	1.13	563	$19.93	0.068	$18.31	$38.24
New, Set @ 5	499	1.50	749	$26.51	0.091	$24.36	$50.87
New (65% Set @ 2, 35% Set @ 5)	499	1.26	629	$22.25	0.076	$20.44	$42.70
Savings, Total Program			578	$20.46	0.070	$18.79	$39.25

A larger control setting compliance survey might reveal the changed settings at the Adams development to be aberrant and that compliance is as good as in Ravenswood (see Table 4.2 and discussion in Section 4.3). If so, then the savings estimate resulting from a weighted average of 87% at 2 and 13% at 5 would increase about 7% to 619 kWh/yr ($42.06/yr).

The effect of the campaign to adjust the control settings is illustrated in Table 4.5. First we estimated savings that would have occurred with the new refrigerators at the average control settings *before* the campaign (15% at 2 and 85% at 5, as shown from NYPA's compliance survey in Table 4.2). The savings from the control adjustment program are then the difference between the savings for the total program and the savings without control adjustment, 93 kWh/yr (16%) of the 578 kWh/yr.

Table 4.5. Savings from Control Adjustment Campaign

Refrigerator Group	Label kWh/yr	Label Ratio	Energy kWh/yr	Energy $/yr	Demand kW/mo.	Demand $/yr	Total $/yr
Existing	903	1.34	1207	$42.71	0.147	$39.24	$81.95
New (15% Set @ 2, 85% Set @ 5)	499	1.45	721	$25.54	0.088	$23.46	$49.00
Savings Est., No Control Adjustment			485	$17.17	0.059	$15.78	$32.95
Savings, From Control Adjustment			93	$3.29	0.011	$3.02	$6.30
Savings, Total Program			578	$20.46	0.070	$18.79	$39.25

5.0 Conclusions

Key results of the analysis are summarized below.

- Early data showed that ***the manufacturer's control settings for the new refrigerators (they were set to 5 on a scale of 9) were producing very cold temperatures. NYCHA subsequently adjusted the new refrigerators downward to 2***, residents received fliers explaining the advantages of keeping them there, and NYCHA staff added this as an item of their annual inspection process.

- ***If all the new GE refrigerators had remained at a control setting of 2,*** the project would have ***saved an average of 644 kWh/yr, worth $43.71 per year per refrigerator*** when demand costs are included.

- NYPA's survey revealed ***an average control setting of 3.06 (after the awareness campaign to keep them set at 2), resulting in estimated savings of 578 kWh per year and an average savings of 0.070 kW at peak demand per month (±10%, 90% confidence interval).*** The cost savings of $39.25/yr represent a 9.1-year simple payback on the $356 cost for purchase, installation, and recycling of the new energy-efficient refrigerators (excluding overheads).

- ***A larger control setting compliance survey might reveal that the changed settings at the Adams development are aberrant*** and that compliance is as good as in Ravenswood (see Table 4.2 and discussion in Section 4.3). ***If so, then the savings estimate*** resulting from a weighted average of 85% at 2 and 15% at 5 ***would increase about 7% to 619 kWh/yr ($42.06/yr).***

- For the 10 buildings whose load data were examined, peak loads occur at approximately 9 pm in the summer and 7 pm in the winter. For the 17 refrigerators metered at 15-minute intervals, the average annual ***load for these peak hours was 1.064 times higher than the average load.***

- ***NYCHA considers its energy cost on the basis of an effective blended rate of $0.085/kWh. For the refrigerators, a similar blended rate*** can be computed as ***$0.068/kWh***. The blended rate for refrigerators is lower because the buildings' total load during peak hours was about 1.6 times the average, while the refrigerators were much closer to their average load (1.064 times).

- It should be noted by other agencies contemplating similar programs in other areas that ***these savings would be much higher where electricity prices are above average***. Also, ***savings will increase in subsequent years as replacement refrigerators get more efficient*** (the 1997 refrigerator has tested energy consumption of 408 kWh/yr, an 18% improvement over the 1996 refrigerator analyzed here).

- NYPA records show ***20,000 GE refrigerators were delivered*** to NYCHA housing developments in 1996. Planergy shows 15,939 old refrigerators were removed.

- ***The new refrigerators are significantly larger than the average replaced unit (14.4 ft^3 compared to 12.6 ft^3).*** This provides considerable added amenity for the residents. It should be noted that savings would be even higher if the new refrigerators were the same size as the existing units. Energy consumption is not strictly linearly proportional to refrigerator size, but a simple estimate of the effect can be based on the ratio of their volumes. ***If the new refrigerators had been as small as those replaced there would have been an additional energy savings of 172 kWh/yr per refrigerator.***

- Another similar qualitative ***amenity provided by the new refrigerators is automatic defrost. Most of the existing units are manual defrost*** models. A simple comparison of the difference in historical DOE-label ratings for refrigerators of this size provides ***an estimate of the energy consumed by a refrigerator automatic defrost cycle: around 140 kWh/yr.***

- ***The apartments are very warm on average, even in winter.*** This is because the units do not have heating thermostats, and the superintendents are required to meet temperature requirements in the coldest apartments. The average indoor air temperature was about 77°F during winter months; summer temperatures rose to an average of 83°F in July. Our savings estimates were based on ***an average annual indoor temperature of 78.7°F.***

- ***Because heating is relatively uncontrolled*** (and supplied by inexpensive natural gas), ***and because air conditioning is not provided, heating and cooling interactions were not factored into savings estimates.***

- The ***warm indoor temperatures actually increase savings***, because, although energy consumption in both the new and existing units increase with warmer indoor temperatures, the existing units increase faster because they are not insulated as well.

- Previous ***studies of refrigerators in single-family dwellings showed the ratio of consumption to DOE-label rating to be about 0.9***, whereas ***in this study the new and existing units have ratios of 1.3.*** Single-family dwellings are typically much cooler than the annual average for the NYCHA apartments (78.7°F), have larger refrigerators, and may have fewer occupants, especially fewer home during the day. The ***difference in temperature explains a little more than 75% of the difference in the ratios; the remaining 25% may be explained by the number of occupants and variations in occupant behavior*** (e.g., number of times the refrigerator door is opened). These issues will be addressed in 1997.

- The ***average weighted (fresh-food and freezer) compartment temperature in the existing sample was 39.3°F. The new units ran a few degrees cooler when operated at the manufacturer's factory control setting of 5.*** The weighted average temperature was 1.2°F cooler; the ***freezer compartments were 2.5°F cooler. It was this observation that led to the campaign to adjust the control settings.*** The cooler freezer compartments in the new refrigerators, in particular, may be caused by a poor setting for the splitter damper that allocates cold air to the two compartments.

- The savings resulting from changing the manufacturer's recommended control setting were estimated at 93 kWh/yr per refrigerator, or about 16% of the total savings from the program.

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Appendix A

Interior Refrigerator Temperature Measurement Discussion

Appendix A

Interior Refrigerator Temperature Measurement Discussion

A series of comparative measurements using both an infrared scanner and a thermocouple were made in the freezer and refrigerator compartments of a set of installed refrigerators. The infrared scanner was an Exergen microscanner model D501. It was set to record the minimum temperature during a scan and hold that value in memory. All exposed surfaces in each compartment were then scanned and the value for the lowest surface temperature was recorded.

The thermocouple measurements were made with a small thermocouple wire (the Fluke #52 meter) having a time constant of several seconds. The refrigerator door was opened and closed quickly to enclose the thermocouple in the chamber for 5 minutes (or until steady-state was reached). A reading was then recorded.

A comparison of the two sets of measurements is plotted in Figure A.1. The higher group of points are from fresh food compartments, the lower group are from freezer compartments. The optical sensor shows good agreement with the thermocouple in the refrigerator compartment but significantly higher (than the thermocouple) readings in the freezer. This may result from a partial fogging of the freezer air and a corresponding impact on the scanned measurement. Better correlation might be achieved in future measurements if the scanner is placed in contact with an exposed surface. Also, it is known that the infrared scanner is biased by differences between the ambient temperature (that the scanner electronics have come to equilibrium in) and the surface temperature that it is measuring.

The points in Figure A.1 are regressed to form a linear correction relationship for scanned measurement. However, because of logistical limitations in the collection of the site temperature measurements (refrigerator, freezer, and ambient), it was not considered appropriate to apply this relationship to adjust the temperatures. All temperature measurements are left as recorded in the field.

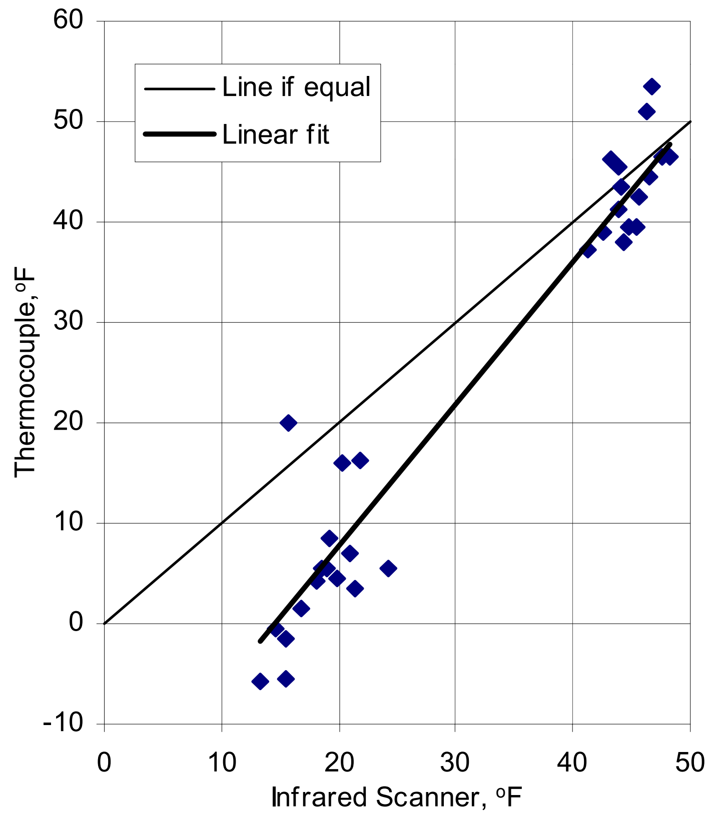

Figure A.1. Comparison of Infrared Scanner and Thermocouple Sensor Measurements

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Appendix B

Temperature Difference Adjustments to Annual- and Population-Average Conditions

Appendix B

Temperature Difference Adjustments to Annual- and Population-Average Conditions

The impact of temperature on consumption can be broken into two components: conduction loads through the refrigerator envelope and cool-down loads. Cool-down loads result from cooling food and air associated with door openings (occupant interactions). Both of these components increase with increasing ambient temperature. The efficiency with which the unit satisfies the conduction load depends on the thermal resistance in the unit's shell and also on the COP of the compressor. The cool-down load is addressed mainly by the compressor. One approach to temperature correction is to analyze the two components separately in a non-linear approach. The other is to analyze their combined effect in a linear method. Both of these methods are discussed in the following sections, and the reasons for selecting the linear method are described.

B.1 Conduction (Non-Linear) Correction

The change in conduction loads associated with a change in operating temperatures can be estimated from DOE-label type chamber testing (no door openings). As shown in Figure B.1, chamber data on the new units was taken over a range of operating conditions and then used to form a non-linear relationship between annualized consumption and ΔT -- the difference between ambient (chamber) and internal (compartment-surface-area weighted) temperature.

Each point in Figure B.1 represents a consumption test at controlled ambient conditions. Consumption is recorded between the end of one defrost cycle and the end of the next.[a] The consumption total during this test is then annualized based on the runtime. Testing at lower ΔT reduces conduction loads and corresponding consumption.

The curve in Figure B.1 represents the total response in annualized consumption caused by changes in loading, COP, and associated defrost energy as effected by ΔT. Consumption approaches zero as ΔT approaches zero. This is equivalent to saying that, as the room temperature approaches the set-point temperature in the refrigerator compartment, the conduction load approaches zero. This is because freezer compartment temperatures are not thermostatically controlled, but instead float in response to cooling done to maintain a set-point in the refrigerator compartment. As the load on the refrigerator

(a) Refrigerator defrost events are triggered by a timer. The timer initiates a defrost cycle when the compressor runtime exceeds a set amount.

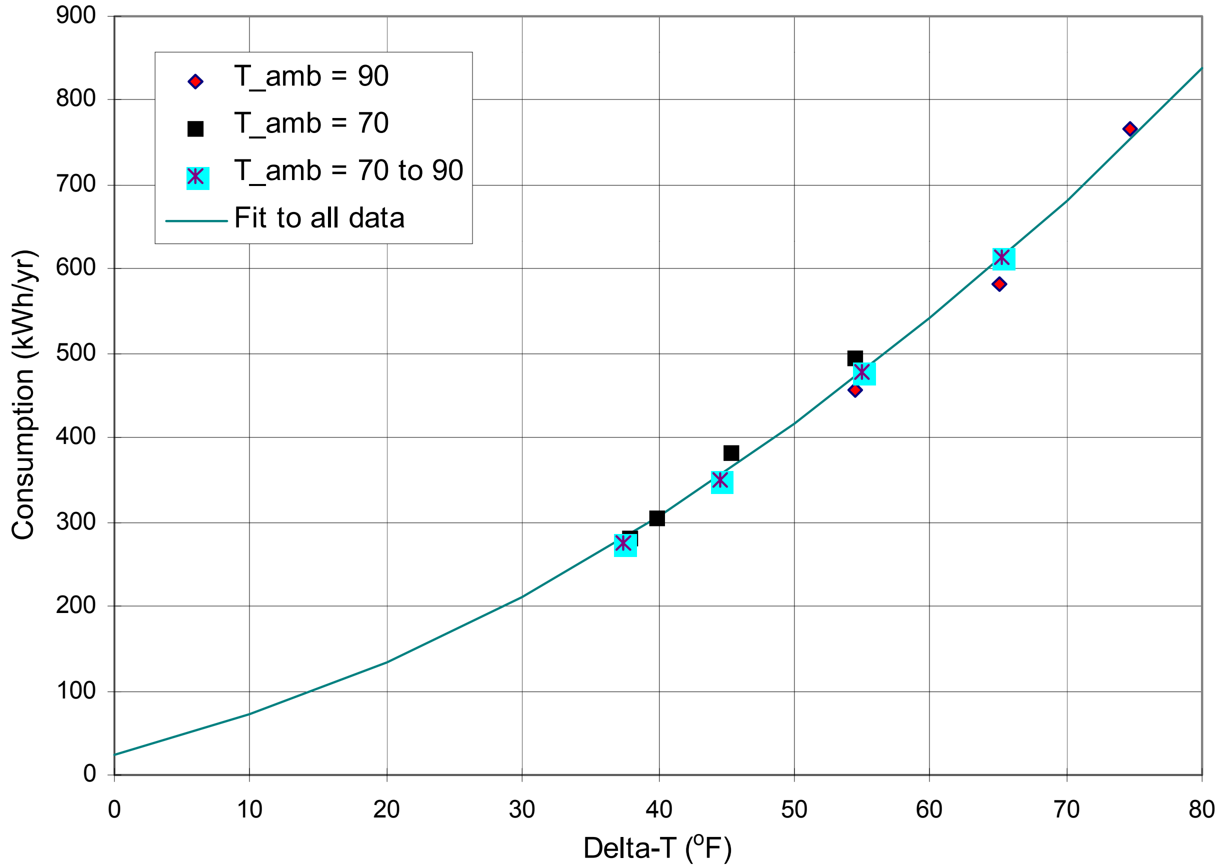

Figure B.1. Relationship of Annualized Consumption and Temperature Difference

compartment approaches zero, the temperature in the freezer compartment approaches that of the refrigerator. The curvature in the plot is believed to be partially the result of the non-linear COP behavior of the compressor.

The change in conduction-related energy consumption is estimated as the change in this curve between two ΔT points (Equation B.1).

$$\Delta E_{conduction_{NEW}} = F(\Delta T_{target}) - F(\Delta T_{actual}) \tag{B.1}$$

where: $\Delta E_{conductionNEW}$ = temperature based correction to annual conduction loads, kWh/yr
F = regression function relating annualized consumption and ΔT
ΔT_{target} = target differential between ambient and internal temperature, ^oF
ΔT_{actual} = actual differential between ambient and internal temperature, ^oF.

If it is assumed that the general shape of the curve is similar for all refrigerators, the function F can be generalized for use with the existing units through use of a label-based correction factor (Equation B.2).

$$\Delta E_{conduction_{OLD}} = \left(\frac{L_{old}}{L_{new}} \right) \left(F(\Delta T_{target}) - F(\Delta T_{actual}) \right) \qquad \text{(B.2)}$$

where: $\Delta E_{conduction\ OLD}$ = correction to conduction loads for existing refrigerators, kWh/yr
L_{old} = label rating of a particular existing refrigerator, kWh/yr
L_{new} = label rating of the new refrigerator, kWh/yr.

Corrections to the cool-down component of consumption are more difficult to estimate, mainly because it is not possible to determine the relative contribution from cool-down and conduction in a simple monitored energy total. The primary data loggers used sampled energy usage and recorded only the total energy. Therefore the project's sample of gross energy consumption can not be directly corrected for cool-down effects.

Even with more detailed data (such as that from the 15-minute data loggers, there remains an obstacle to making temperature corrections on the cool-down component. Information on compressor COP (as a function of internal and ambient temperature) is needed.

To circumvent the difficulties in projecting the cooldown component, it can be assumed that corrections to the cooldown component are, on average, equivalent for both the new and existing units. The impact of this assumption is that when calculating differential consumption (savings), the temperature corrections to the occupancy effects drop out of the analysis. Therefore, corrections to savings estimates can be based strictly on corrections to the conduction component.

This simplifying assumption depends on three underlying assumptions: (1) the COP characteristics of the new and existing units are equal; (2) on average, the occupant behavior generating the cool-down loads is equal for both the new and existing refrigerators; and (3) when projecting to a common temperature, any differences between the original sample-average temperature of the new and existing units is small.

The final annual consumption is calculated as

$$E_{corrected} = E_{raw} + \Delta E_{conduction} + \Delta E_{cooldown} \qquad \text{(B.3)}$$

where Equation (B.2) is used for existing units. It must be emphasized that any corrected energy consumption, calculated with a conduction correction, does not include the $\Delta E_{cooldown}$ correction. It is not available for calculation (as explained above, the cooldown fraction and COP data are not available) and therefore it can not be included. These corrected results are not to be used as absolutes but only as input to savings calculations.

If the simplifying assumptions above are incorporated, the cooldown component is eliminated in savings calculations:

$$
\begin{aligned}
E_{savings} &= E_{corrected_{OLD}} - E_{corrected_{NEW}} \\
&= (E_{raw_{OLD}} - E_{raw_{NEW}}) + (\Delta E_{conduction_{OLD}} - \Delta E_{conduction_{NEW}})
\end{aligned}
\tag{B.4}
$$

B.2 Pure ΔT (Linear) Correction

Lacking detailed information on cooldown fraction and refrigerator COP characteristics, there is an alternate simplified approach to temperature correction. This is done by keeping the two load components together and making an approximation that total consumption is proportional to ΔT.

Each observed field consumption can be projected to a new ΔT as shown in Equation (B.5). If the ΔT increases by 25%, the projected consumption increases by the same 25%.

$$
E_2 = E_1\left(\frac{T_{a\_2} - T_{i\_2}}{T_{a\_1} - T_{i\_1}}\right) \tag{B.5}
$$

This approximation asserts that for a given fractional increase in ΔT, both the energy consumption associated with the conduction component (compressor and related defrost energy) and the energy consumption associated with the cooldown component (compressor and related defrost energy) will have the same fractional increase. Underlying this assertion is the assumption that similar to the conduction component, the cooldown component approaches zero as ΔT approaches zero. This is equivalent to stating that the majority of warm food placed into the refrigerator is at a temperature near ambient (hot food is generally left to cool first before storing in the refrigerator; food recently purchased at the store will either be at room temperature or near refrigerator or freezer temperatures; and warm air entering the refrigerator will by definition be at ambient temperature).

Also it assumes that non-linear variations in consumption, mainly relating to COP, are not significant. Support for this assumption can be found in Figure B.1. It shows that the conduction-related consumption is strongly correlated with ΔT, and that variation in COP (with changing ambient or internal temperature) is responsible for only slight curvature over the range of interest.

This approach is especially compelling because it greatly reduces the requirements for data and the complexity of the analysis.

- No estimates are needed for the cooldown component. Both components are corrected in the same simplified (proportional to ΔT) approach. There is no need to separate them.
- No label rating is needed. This projection method works equally well for new and existing units.
- No chamber testing results are used.
- No detailed metering of power consumption is used.

- No COP data is used.

- This approach can be used in producing absolution consumption numbers for both the new and existing units. This is unlike the conduction-correction method, which is limited to producing input for savings calculations (difference between new and existing units).

It should be noted that this simplified linear analysis can be used in calculating savings and compliments the non-linear methodology. Both the linear and the conduction-correction methods are somewhat limited by assumptions; however, the two approaches produce nearly identical savings results in this analysis. When looking at absolute consumption, the linear approximation is preferred because corrections to the cooldown effects are automatically included in the accounting.

B.3 Projection to Other Sites

While the linear ΔT approach is compelling for this analysis, it is fundamentally limited when projecting to other locations. This is because projecting to a different location involves not only projecting to different operating temperatures but also possibly to different user characteristics, e.g., strongly different door-opening behaviors. In terms of equations presented above, different user behaviors may have a different X_{cd} (cooldown fraction of total consumption). The ΔT approach is only valid if this fraction is on average equal for the sample and the population that it represents. This is simply because the conduction and cooldown components are not separated in the analysis.

In principle, the conduction-correction approach outlined above could be extended to accommodate a different X_{cd} at the projected site. The conduction term can be projected based on the operating temperatures. The cooldown term would be estimated at the new site based on some site/culture specific sample of door-opening behavior and a site-independent relationship between consumption and door-opening events.

B.4 Estimate of Annual Average Ambient Temperature

The temperature correction methods are implemented in this analysis by determining target temperatures to which the field results are projected. In the analysis tool, target internal temperature can either be set to a user-determined value including the average of the field sample or left as the actual measured internal temperatures. This feature, for example, can be used to test the sensitivity to changes in refrigerator control settings. Unless specified differently, for all the results reported, the internal target is set to equal the average of the field sample. This reflects the fact that internal temperatures are not strongly affected by changes in seasons and associated changes in the room temperature.

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Appendix C

Demand Impact Estimation

Appendix C

Demand Impact Estimation

Demand charges for the refrigerators in this program are calculated based on their contribution to the building load at the time of building-peak power usage. Estimates of demand charges are calculated as shown:

$$D = P_{average} F_{peak/average}(t_{coincident}) R \bullet 12 / 1000$$

where:

D = annual coincident demand charge.
$P_{average}$ = total-average power draw (for each model), W
$F_{peak/average}$ = ratio of hourly-average to total-average (by time of day)
$t_{coincident}$ = time of day for building peak (coincidence information)
R = demand rate, \$/kW-month.

$P_{average}$ is based on gross power-usage records (either metered or modeled) for each model of refrigerator and is simply the annual load estimate divided by the number of hours in a year.

$$P_{average} = \frac{E_{annual}}{8760}$$

where: E_{annual} = annualized energy consumption (kWh/yr).

The $F_{peak/average}$ is determined from detailed field monitoring on 17 refrigerators (each logged at 15-minute intervals for 6 or more days). A plot of $F_{peak/average}$ is shown in Figure 4.5 (in Section 4.5 of the main body of this report) as a function of time of day. Each point on this plot is determined by the average consumption for a specific hour divided by the average consumption for all 24 hours.

To remove cycling variations (and anomalous contribution to the load shape), the individual time series data are first smoothed. This is done by substituting the average values resulting from a moving 75-minute[(a)] window.

(a) The duration of the moving-average window is 75 minutes for the majority of the 17 units processed. Longer windows (up to a maximum of 4 hours) were used for those refrigerators with long cycle periods.

Each of the 17 time series is averaged by hour of day. These 17 load shapes are then given equal weight in determining the overall average load shape shown in Figure 4.5. This averaging of the averages is necessary to avoid giving higher weight to the apartments with longer monitoring periods (some were monitored for approximately 2 weeks).

Also shown in Figure 4.5 is the average that results if no pre-smoothing is done (trace labeled "Raw"). The difference between the pre-smoothed and raw traces is caused by the small sample size. As metering increases beyond 17 units, cycling variation will naturally be removed in the time-of-day averaging process and the "raw" sample averages will approach the "pre-smoothed" result.

The 17 refrigerators were monitored for a week each during the period January to September. If the results are separated by season, winter (with start dates ranging from 1/5 to 2/17) and summer (start dates ranging from 5/23 to 9/12), the load shapes appearing in Figure C.1 result. (Both traces have pre-smoothed data).

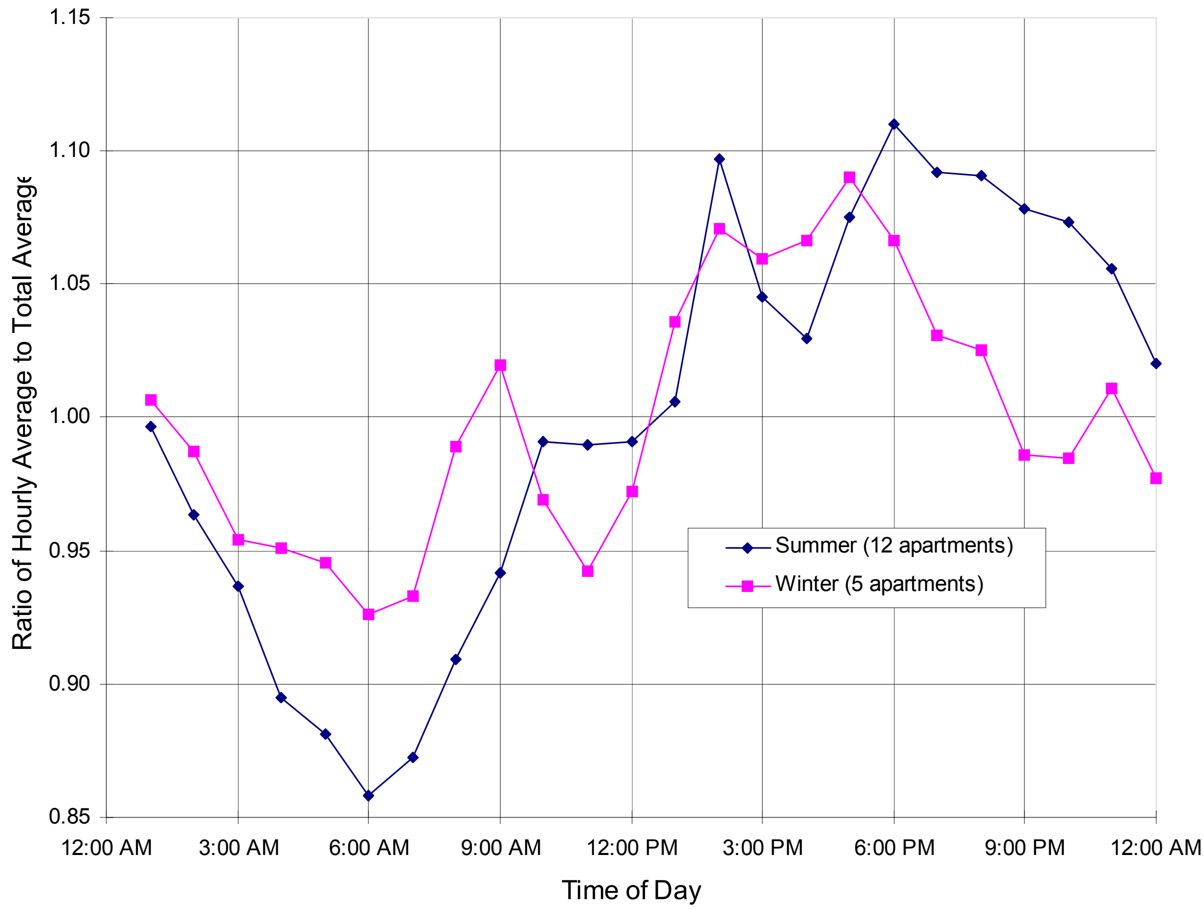

Figure C.1. Load Shape by Seasons

$F_{peak/average}(t_{coincident})$ is then determined as the value of $F_{peak/average}$ at the time of building peak consumption. This can be done for both summer and winter period using the average of building peak-time data from 10 buildings. However, because of the small amount of detailed metering done during the winter season, the lumped load shape (Figure 4.5) is used for both the summer and winter seasons. The result is shown in Table C.1 with a summer coincident-peak-to-mean ratio of 1.050 and a winter coincident-peak-to-mean ratio of 1.078. The average of these two values, 1.064, is used to represent the whole year.

Table C.1. Summer/Winter Building Peaks and Coincident Peak-to-Average Refrigerator Ratios

Complex	Summer Peak	Winter Peak
Jackson	9:15 PM	6:15 PM
Rutgers	8:15 PM	6:30 PM
Morris	9:00 PM	8:00 PM
Pink	8:45 PM	5:30 PM
Bronx River	9:45 PM	6:45 PM
Isaacs	8:30 PM	6:45 PM
Butler	9:15 PM	7:15 PM
Mitchell	9:15 PM	7:30 PM
Barach #18	8:00 PM	6:45 PM
Adams	9:45 PM	6:45 PM
Average	8:58 PM	6:48 PM
Coincident	1.050	1.078

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Appendix D

Confidence Interval Estimation

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Confidence Interval Estimation

Confidence intervals for the estimate of savings can be determined through a stratified analysis of sample mean and variance (Cochran 1980). In a stratified analysis, the mean and variance of each strata are weighted by records of strata population to produce estimates of the mean consumption and the corresponding variance for the existing units. This is also done for the single-stratum population of new units. Together, they combine to produce an estimate of program savings and a confidence interval.

D.1 Mean Values

The estimate of the mean for the population of **new** refrigerators is simply the average of the sample of n new refrigerators.

$$\overline{E}_{replacement} = \frac{1}{n}\sum_{k=1}^{n} E_k \tag{D.1}$$

The estimate of the mean energy consumption of the population of *existing* refrigerators is the total of all contributions to the mean from each stratum as weighted by population fraction.[(a)] A mean, $\overline{E}_i$, is determined for each stratum using the consumption model. These means are then weighted by the corresponding population fraction and then summed.

$$\overline{E}_{existing} = \sum_{i} W_i \overline{E}_i \tag{D.2}$$

where the weighting factor W_i is the fraction of the total population in stratum i, (N_i); N = total population.

$$W_i = N_i / N . \tag{D.3}$$

(a) These (strata) calculations produce mean values equivalent to those presented in Section E.6.

D.2 Savings and Confidence Intervals

The estimate of savings and the corresponding confidence interval is calculated as shown. The savings is simply the difference between the estimated mean of the existing and new units. The standard error of the savings is calculated as the root of the sum of the squares of standard error for the existing and new units. The confidence interval is then the product of the savings standard error and the Student's t factor for n_{df} degrees of freedom.[a]

$$E_{savings} = \overline{E}_{existing} - \overline{E}_{replacement} \pm \left(\sqrt{s^2(\overline{E}_{existing}) + s^2(\overline{E}_{replacement})}\right) \bullet t_{st}(n_{df\_savings}) \qquad \text{(D.4)}$$

where: $t_{st} =$ t values from Student's distribution for n degrees of freedom.

The estimate of the standard error for the population of existing units is taken as the population-weighted sum of contributions to standard error by each stratum (Equation D.5). Here the standard error from each sampled stratum is weighted by the population fraction, squared, summed over all strata, and then the square root is taken.

$$s(\overline{E}_{existing}) = \sqrt{\sum_i W_i^2 \frac{s_i^2}{n_i}} \qquad \text{(D.5)}$$

where:

$s(\overline{E}_{existing})$ = standard deviation of the mean of $E_{existing}$ (i.e., standard error)

$\sqrt{s_i^2 / n_i}$ = standard error of sample in stratum i

s_i = standard deviation of sample in stratum i.

This equation (D.5) is also applied to the single stratum for the new units (only one type of new model at this point in the project). For a single stratum, it reduces to the usual expression for standard error (standard deviation over the square root of n).

An estimate of the standard error for each existing-unit strata is made through use of the consumption model and the strata label rating (Neter and Wasserman 1974).

$$s(\widehat{Y}_i) = \sqrt{MSE\left[\frac{1}{n} + \frac{(X_i - \overline{X})^2}{\sum_j (X_j - \overline{X})^2}\right]} \qquad \text{(D.6)}$$

(a) In this study the final sample of existing units was sufficiently large such that t values can be replaced with z values from a table of normal distribution. For example, the normal z value for 95% confidence is 1.96 and for 90% is 1.64.

where:

$$s(\hat{Y}_i) = \text{estimated standard error for stratum i}$$

$$\hat{Y}_i = \text{estimated mean value for stratum i}$$

$$MSE = \frac{\sum_j (Y_j - b_0 - b_1 X_j)^2}{n-2}$$

X_i = label rating in stratum i

$\overline{X}$ = average label rating of the sample of existing refrigerators

X_j = label rating of observation j in the sample of existing refrigerators

n = number of observations in the sample of existing refrigerators.

D.3 Population Weighed Results

Table D.1 presents the results of the population-weighted calculations.[a] The actual stratum count is shown in the column labeled "Population," the population-weighted mean is shown in the top two rows of the column labeled "Corrected Energy," and the population-weighted standard error is shown in the column labeled "StdErr^2." The algorithms for determining these results are described in the preceding two sections.

The first row, below the New and Existing summary rows, represents all of the population that does not fall into metered strata (5,892 units). Essentially, this is a lumped stratum composed of many different strata as defined in Section E.4. This row is processed differently than the rows below it because it is composed of units of different label ratings and because of the non-linear nature of the calculation for stratum standard error (Equation D.6). Because of this, Equation D.6 is actually applied to each un-metered stratum and weighted as shown in Equation D.5. The result is shown in this first row. This row is not simply the application of Equation D.4 to the population-weighted label (858 kWh/yr) of all the unmetered strata.

(a) The sample size shown here for the existing refrigerators is only 15,832 instead of 15,979, because there were slightly fewer model numbers of demanufactured refrigerators recorded than the number demanufactured by Planergy.

Table D.1. Population-Weighted Stratum Calculations

Stratum (-)	Pop-ulation (-)	Pop. Weight (-)	Sample Std Error (-)	Modeled Std Error (-)	DOE Label (kWh/yr)	Label Ratio (-)	Corrected Energy (kWh/yr)	Field Count (-)	StdErr^2 W^2*s^2/n (-)
90% Confidence interval on savings = 644 +/- 63 kWh/year (+/- 10% of savings)									
New	15832	1.000			499	1.13	563	34	600
Existing	15832	1.000			903	1.34	1207	182	862
1	5892	0.372	45	63	857	1.33	1140	15	552
4	27	0.002	123	80	503	1.25	628	3	0
10	28	0.002	43	71	552	1.27	699	2	0
18	130	0.008	331	68	567	1.27	721	4	0
23	485	0.031	107	59	624	1.29	803	33	3
30	119	0.008	94	48	697	1.30	909	6	0
34	89	0.006	42	45	725	1.31	949	3	0
36	136	0.009	80	44	733	1.31	961	8	0
37	94	0.006	52	44	735	1.31	963	7	0
39	241	0.015	105	43	740	1.31	971	3	0
40	248	0.016	89	43	740	1.31	971	4	0
41	65	0.004	306	42	759	1.32	998	2	0
42	0	0.000	40	42	765	1.32	1007	2	0
44	199	0.013	277	41	770	1.32	1014	2	0
45	13	0.001	125	41	784	1.32	1034	3	0
48	42	0.003	10	41	785	1.32	1036	2	0
57	138	0.009	182	40	815	1.32	1079	2	0
58	1,026	0.065	37	40	824	1.33	1092	4	7
59	361	0.023	198	40	828	1.33	1098	4	1
61	98	0.006	99	40	828	1.33	1098	9	0
62	51	0.003	186	40	835	1.33	1108	4	0
71	670	0.042	47	43	885	1.33	1180	4	3
78	205	0.013	123	45	905	1.34	1209	5	0
79	236	0.015	145	47	924	1.34	1237	3	0
80	110	0.007	53	47	925	1.34	1238	7	0
83	554	0.035	142	52	965	1.34	1296	6	3
92	82	0.005	238	65	1044	1.35	1410	3	0
93	814	0.051	98	66	1046	1.35	1413	12	11
95	3,679	0.232	246	72	1080	1.35	1462	20	277

F.Level 1 Heading

THIS PAGE CONTAINS A LEVEL 1 HEADING WHICH ACTIVATES THE APPENDIX LETTER IN THE PAGE NUMBER. THE HEADING 1 STYLE MUST BE MODIFIED IN ORDER TO CHANGE THE APPENDIX LETTER.

PLEASE RECYCLE THIS PAGE.

Appendix F

Comparison of the Label Ratios to Those from Other Programs

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Comparison of the Label Ratios to Those from Other Programs

Refrigerator field energy consumption (expressed as a ratio to the DOE-label ratings[a]) observed in this program is significantly higher than what has been observed in other studies. The issue is that the raw field data shows consumption/label ratios of 1.34 for all existing units and 1.16 for new units (new unit controls set to level 2). These ratios stand in contrast to the reported ratio of 0.89 from the Bonneville Power Administration's End-Use Load and Consumer Assessment Program (ELCAP) field monitoring program (Ross 1991). Factors that explain high ratios in the NYPA study are discussed in the following sections.

F.1 Temperature

The estimated annual-average indoor daytime temperature for the apartments monitored by the program is 78.7°F. This is significantly higher than the 69°F average-indoor temperature reported in the ELCAP study of single-family housing.

Table F.1 shows the consumption/label ratios that result from applying a linear temperature correction (see Section B.2) to the field data.[b] The raw field sample (uncorrected and unweighted by new unit populations) is shown in the first row. The average ΔT is shown in brackets ([]). In the second row, each unit in the sample is projected to the annual-average ambient conditions of 78.7°F for both new and existing units (ambient projection only, internal temperatures left as recorded in the field monitoring). In the third row, the sample of existing units is weighted by the corresponding populations of existing units removed from the housing developments. In the fourth row, the projection is to an ambient temperature of 69°F.

(a) DOE-label ratings refer to controlled consumption testing (no door openings) at an ambient temperature of 90°F. These label ratings are not intended to accurately predict field consumption but rather serve in a way analogous to miles-per-gallon ratings for automobiles.

(b) Some of the label ratios shown in Table E.5 are slightly different than those reported in the body of the report. This is because those reported here are the average of the individual label ratios, whereas those reported in Section 4 are the average consumption divided by the average label ratio.

Table F.1. Consumption/Label Ratios for Various Conditions

Condition	Existing Refrigerators	New Refrigerators
Raw sample	1.35 [$\Delta T = 39.8\ ^oF$]	1.15 [$\Delta T = 42.5\ ^oF$]
Projected to 78.7 ^oF	1.33 [$\Delta T = 39.4\ ^oF$]	1.13 [$\Delta T = 41.5\ ^oF$]
Projected to 78.7 ^oF & weighted	1.33 [$\Delta T = 39.4\ ^oF$]	1.13 [$\Delta T = 41.5\ ^oF$]
Projected to 69.0 ^oF & weighted	1.00 [$\Delta T = 29.7\ ^oF$]	0.86 [$\Delta T = 31.8\ ^oF$]
Difference (in 2 rows above)	0.33	0.27
Percent of discrepancy	0.33/(1.33-0.89)=75%	0.27/(1.13-0.89)=112%

Using this method, the temperature effect accounts for approximately 75% of the original discrepancy for the existing units and 112% for the new units. However, it must be noted that this assumes temperature control settings of 2, reducing the label ratios for the new units. The observed control settings were closer to 3.06, resulting in a label ratio of 1.26. Consequently, the field-measured label ratios would be higher, and the temperature effect would account for only about 81% of the discrepancy after projection to the 69^{o}F ambient.

F.2 Refrigerator Insulation Levels

Another distinct characteristic of the field sample, which can cause relatively high consumption/label ratios, is the higher-than-normal levels of insulation in the new units. This is because label-testing procedures do not measure door-opening effects. Imagine a perfectly insulated refrigerator. It would have a label rating of zero from chamber testing, yet, in the real world, door-openings and associated food and air cooldowns would result in cooling loads on the compressor. In this perfect-refrigerator extreme, the ratio of consumption to label would be infinite.

As a refrigerator's insulation level increases, the fraction of total consumption that is related to cooldown loads gets higher (assuming the compressor technology remains the same). It is reasonable to expect that this could account for any of the remaining difference between this program and the ELCAP study.

For the existing units, this high-insulation argument does not apply. However, there may be a similar, but only second-order effect related to the relatively small size of the existing units in the developments. If it is assumed conductive loads decrease faster with volume than cool-down loads, the same argument could be used to make the case that smaller refrigerators would tend to have higher consumption/label ratios than larger ones. However, this assumption is debatable and probably does not account for a significant fraction of discrepancy for the existing units.

F.3 Degradation

Finally, the remaining portion of the discrepancy between the consumption levels of the existing units in public housing and those in single-family houses may be attributable to degradation. Factors contributing to degradation include age, lack of maintenance, and manual defrost which may result in more instances of coils being covered with ice and/or insulation becoming wet.

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